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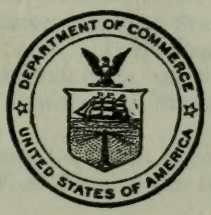

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No. 203

INFLUENCE OF PHOSPHORUS UPON THE MICRO-STRUCTURE AND HARDNESS OF LOW-CARBON, OPEN-HEARTH STEELS

BY

EDWARD C. GROESBECK, Associate Chemist

Bureau of Standards

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INFLUENCE OF PHOSPHORUS UPON THE MICROSTRUCTURE AND HARDNESS OF LOW-CARBON, OPEN-HEARTH STEELS

By Edward C. Groesbeck

ABSTRACT

In this investigation, undertaken with the object of throwing additional light on the rôle played by phosphorus upon the properties of low-carbon, open-hearth steels which are often used in the manufacture of products where severe cold working is employed during fabrication, no clear relationship could be established between the phosphorus content, varying within the range 0.008 to 0.115 per cent, which marks the usual limits in plain carbon steels, and the microstructure and hardness as developed in two series of specimens, one of basic open-hearth steel and the other of acid open-hearth steel, by a series of different heat treatments, because of the marked irregularity in the distribution and grain size of the ferrite and pearlite grains found present in many of the specimens. This irregularity was traced, by means of the microstructure as developed by etching, to the nonuniform distribution of the phosphorus. A cellularlike structure formed in conjunction with the microstructure normal to these steels was studied and relationship between this unusual structure and the distribution of phosphorus was established.

Because of the very limited amount of material available for this investigation it was not possible to extend the scope of the work beyond the study of the microstructure and hardness of the steels in question.

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I. INTRODUCTION

In connection with an investigation made several years ago into the effect of varying phosphorus content upon the endurance qualities of low-carbon steel when severely cold worked, as in stamping, drawing, pressing, upsetting, and bending, Dr. J. S. Unger [1] prepared two series of ingots, one of basic open-hearth steel and the other of acid open-hearth steel, all having the same general composition, but with the phosphorus content varying from 0.008 to 0.11 per cent, and which comprises the range of phosphorus content usually found in acid open-hearth and acid Bessemer steel. These steel ingots were rolled down into the usual billets, slabs, and sheet bar preparatory to the formation by cold work of the various products upon which the tests were made. These steels were given no other than the customary heat treatment accorded ordinary soft steels during the process of fabrication. Through Dr. Unger's kindness, a small quantity of material in the form of 1-inch rounds from the two series of ingots was made available for this study.

There appears to be scant information of a systematic nature in the published literature with regard to the influence of varying amounts of phosphorus, especially within the limits usually found for this element in open-hearth and Bessemer steel, upon the microstructure and physical properties of low-carbon steel as developed by heat treatment. D'Amico published in 1913 [2] the results of an investigation carried out on the microstructure, hardness, mechanical, and magnetic properties as developed by heat treatment in a series of 12 low-carbon steels, made by the electric process, to which phosphorus had been added, so that the resulting phosphorus content varied from 0.012 to 1.242 per cent. Only two of his steels come within the range of phosphorus content covered in this investigation. Dr. Unger [3] stated that in his investigation the effect of heat treatment was not studied, inasmuch as soft steels are rarely heat treated, though he made a few tensile and other tests on some heat-treated bars.

---

[1] J. S. Unger, Proceedings Amer. Iron and Steel Inst., 1918, pp. 172–193; also Iron Age, **101**, p. 1538; June 13, 1918.

[2] E. D'Amico, "Uber den einfluss des phosphors auf die eigenschaften des flusseisens," Ferrum, **10**, pp. 289–304.

[3] See footnote 1.

II. AIM OF INVESTIGATION

The scope of this investigation, undertaken with the hope of throwing additional light on the rôle played by phosphorus upon the properties of the steels in question or, at least, of the ordinary low-carbon steels which are used for the manufacture of products where severe cold working is employed during fabrication, was confined to the relationship between the phosphorus content, as present within the limits 0.008 to 0.115 per cent, and the microstructure and hardness as developed by a series of heat treatments and also the distribution of the phosphorus in the steel as revealed by metallographic etching.

III. PREPARATION OF MATERIAL

1. MATERIAL

The steels used in this investigation were of the following general chemical composition: Carbon, 0.12 per cent; manganese, 0.36 per cent; silicon, 0.020 to 0.022 per cent; sulphur, 0.036 to 0.037 per cent; copper, 0.012 to 0.014 per cent; and phosphorus as below:

Basic open-hearth series	Per cent	Acid open-hearth series	Per cent
Steel A	0.008		
Steel B	.030	Steel BB	0.032
Steel C	.052	Steel CC	.058
Steel D	.080	Steel DD	.085
Steel E	.110	Steel EE	.115

The limited amount of material made available for this study necessitated the use of small samples. Transverse slices one-fourth inch thick were cut from the 1-inch rounds and these slices in turn radially into quarters. Each specimen thus presented a face approximately a quadrant of a circle of one-half inch radius for microscopic examination and hardness determination.

The nine specimens, one from each of the steels in both the B. O. H. and A. O. H. series for each heating, were fastened three in a row to a piece of rather coarse iron wire gauze, which was wrapped around the pyrometer tube at the closed end in such a way that the three rows of specimens were placed approximately equidistant around the outer circumference of and in contact with the pyrometer tube and also so that the hot junction of the chromel-alumel thermocouple, used in conjunction with a millivoltmeter, was approximately centrally located within the cluster of the nine specimens.

2. APPARATUS

All but one of the heatings were carried out in a horizontal tubular nichrome-wound electric furnace, provided with an iron pipe 2¾ inches inside diameter and 27 inches long, over which was slipped a fairly snug fitting alundum cylinder 24 inches long and around which the heating element was wound. The equalization of the temperature within the hotter part of the iron-pipe furnace tube was aided by means of baffle plates, and the specimens to be heated were placed within the portion of the furnace tube found by trial to have the flattest thermal gradient, namely, about 5° C over a distance of 2½ inches. Boats filled with ground charcoal were placed within the furnace tube near both ends in order to counteract the decarburizing conditions as far as practicable. In the lead-bath heating, which was carried out in a gas-fired, lead-bath furnace, the specimens were placed around the nichrome pyrometer protection tube at the closed end in a similar manner as in the other heatings, and this tube was placed in such a position that the specimens were approximately in the center of the molten lead bath, which was about 6½ inches in diameter and 11 inches deep.

3. EXPERIMENTAL PROCEDURE

A series of six heat treatments was made, in which the rate of cooling from the maximum temperature, 900° C, was so regulated that the cooling through the 750 to 600° C range occupied the following periods of time: Four hours, 2 hours, 1 hour, 30 minutes, 15 minutes, and 5 minutes. In all cases the cooling from 900 to 750° C was so controlled that the rate of cooling in this range would correspond as closely as practicable to that followed through the 750 to 600° C range, which was chosen as that in which the formation and the break-up of the lamellar pearlite into "granular" pearlite occurred in order to note whatever influence the phosphorus content might have on this tendency. In the lead-bath heating (HT–7) the gas and air were shut off entirely soon after the maximum temperature, 900° C, was reached, and the cooling of the bath and specimens was allowed to proceed uninterruptedly in the furnace until the temperature of the bath had reached 500° C when the specimens were taken out and allowed to cool in the air.

Fig. 1 shows graphically the heating and cooling curves for all the seven heatings carried out.

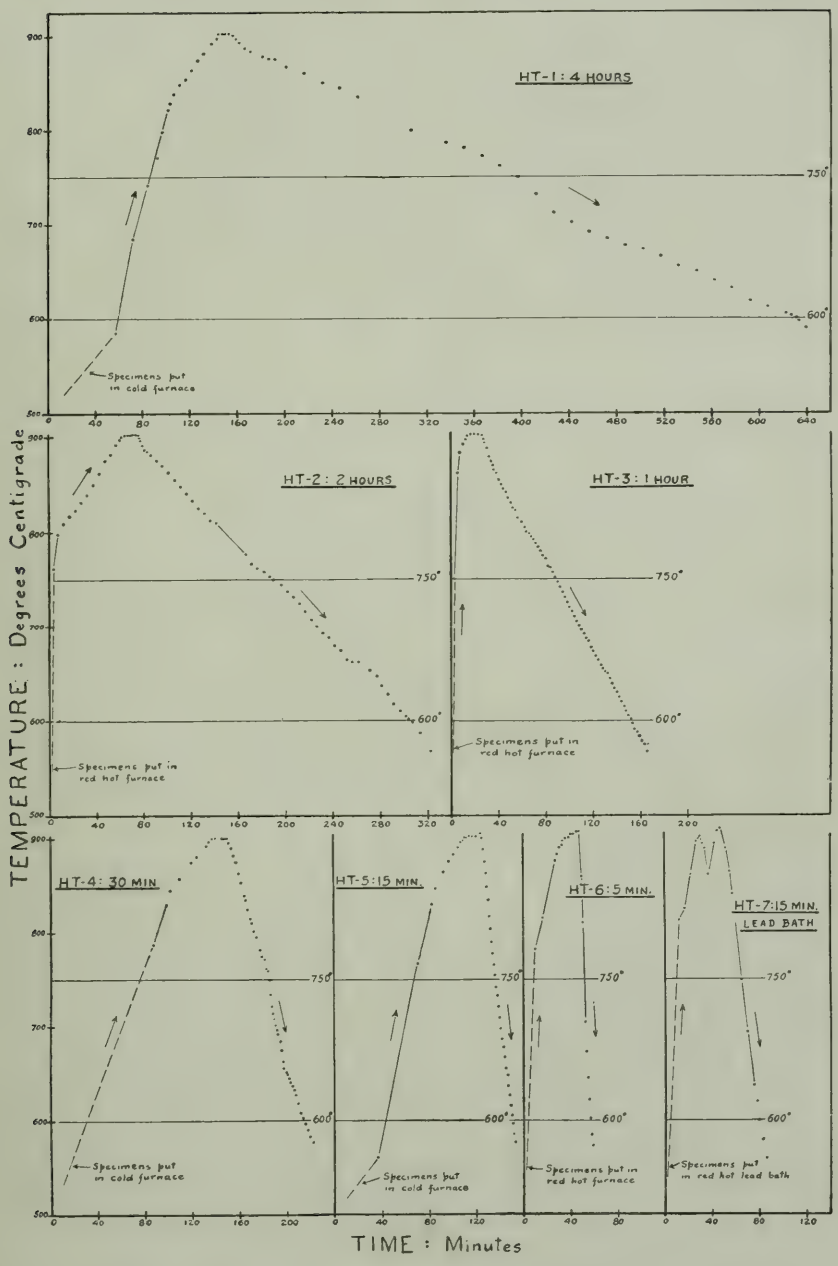

FIG. 1.—*Heating and cooling diagrams for the series of heat treatments carried out*

See Table 1 for the lengths of time covered by the various stages of the heatings and coolings. The times given in the title for each of the diagrams refer to that taken in cooling down through the 750–600° C range.

In Table 1 are given the periods of time occupied by the different stages of the heatings and coolings.

TABLE 1.—Heat Treatment—Times of Heating and Cooling

Laboratory number	Desired rate of cooling through 750–600° C	Condition of furnace on insertion of specimens	Heating interval		Cooling interval	
			To 900° C	At 900° C	900–750° C	750–600° C
	Minutes		Minutes	Minutes	Minutes	Minutes
HT–1	240	Cold	145	12	241	234
HT–2	120	Red hot	61	15	109	116
HT–3	60	do	14	12	61	63½
HT–4	30	Cold	137	12	35	29⅚
HT–5	15	Hot	110	15	11⅓	14⅓
HT–6	5	Red hot [a]	35	14±	2±	6⅙
HT–7	[b] 15	Red hot	42	[c] 10±	16±	15

[a] The pipe container with the specimens was put back into the furnace immediately following a heating to 900° C and cooling down below 500° C, as the cooling through the 750 to 600° C range was found to have been too fast.

[b] Lead bath.

[c] During the holding at 900° C, the air blast stopped for a moment, so the temperature fell from 900° C, where it had been for about four minutes, down to 862° C, and it was raised again to 900° C, remaining at or above that temperature for six minutes more.

In the HT–5, 15 minutes, and HT–6, 5 minutes, heat treatments, an iron pipe 1½ inches in diameter and 10 inches long overall, with iron caps screwed on at both ends, was used as a container for the specimens. Iron rods were fastened lengthwise to the container at the bottom in order to give a clearance between the furnace-tube wall at the bottom and the caps at both ends of the container and to facilitate the passage of air underneath in the 15-minute cooling. The fused silica pyrometer tube was inserted through a hole in the cap at one end of the container. The container was so situated in the furnace tube that the cluster of specimens placed in the center of the container would lie within the zone where the thermal gradient was flattest.

In the HT–5, 15 minutes run, the cooling of the pipe container and specimens was effected by means of a stream of air (laboratory table air blast) introduced through silica tubes placed through both ends of the furnace tube, one directed at the upper edge of one end and the other at the lower edge of the opposite end of the container.

In the HT–6, 5 minutes run, the pipe container was at the start of the cooling shoved out of the furnace tube into a 12-inch long and 3-inch diameter alundum tube surrounded by pipe insulation covering that had been preheated to a couple of hundred degrees

centigrade above room temperature and both open ends of the alundum tube were then immediately plugged up in order to check the outflow of the heat. In this manner the cooling of the specimens through the 750 to 600° C range was so regulated as to take about five minutes.

IV. MICROSTRUCTURE

In the grinding of the heat-treated specimens for microscopic examination and hardness determination ample allowance was made for the decarburization produced during heat treatment, and the extent of which was ascertained by measuring the thickness of the decarburized layer at one edge of a copper-plated and rather heavily ground specimen that had been given the longest heating (HT–1) carried out in the series of heatings.

1. GENERAL STRUCTURE

It was noted from a study of micrographs, taken of all the heat-treated specimens at near each corner of the quadrant-shaped specimen, that there is a marked irregularity in the distribution and size of both the ferrite grains and pearlite kernels in many of the specimens, especially in the A. O. H. steels as compared with that for the B. O. H. steels, and that there is no definite relation between the occurrence of this irregularity of structure and the phosphorus content and heat treatment.

Figs. 2, 3, 4, and 5, which were selected from the steels having the minimum and maximum phosphorus content (the 0.008 per cent phosphorus B. O. H. steel possessed a similar structure and grain size to that of the 0.030 per cent phosphorus B. O. H. steel for all the seven heatings) and were cooled through the 750 to 600° C range in 4 hours, 30 minutes, 5 minutes, and in the lead bath, illustrate in a general way the structure as developed in the different steels by the various heat treatments tried. For the steels of intermediate phosphorus content and cooled at the other rates tried, the structure is similar to that shown for the higher or lower phosphorus content and the more slowly or quickly cooled steels. There were several cases in which there was a marked deviation from the general structure as outlined above, and these cases are indicated in Table 2, where there is a large increase in the average grain area, as compared with that for the more slowly or quickly cooled specimens for the same steel.

It should be borne in mind that the grain size, as shown in Figs. 2 to 5, represents the effect, or rather the grain growth,

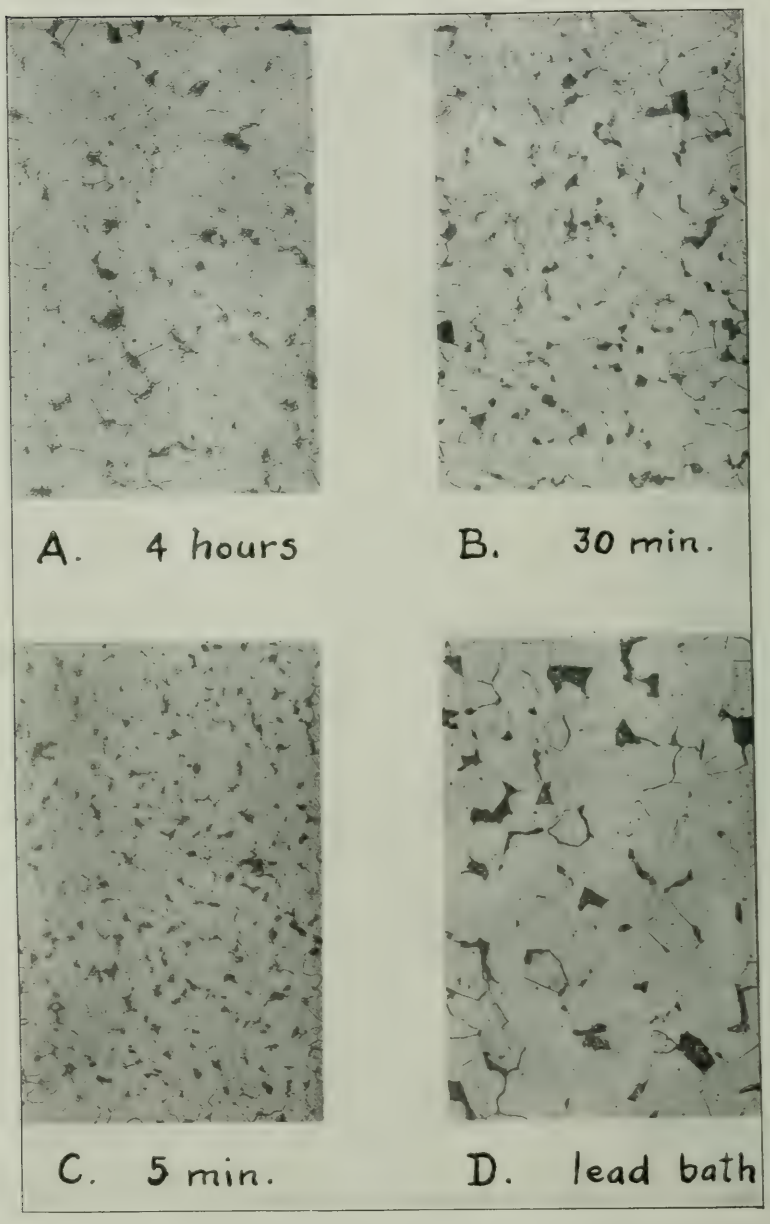

FIG. 2.—*Microstructure of low-carbon basic open-hearth steel containing 0.030 per cent phosphorus.* ×100

Heated to 900° C and cooled through 750–600° C range in the periods of time as indicated. Etching reagent, 5 per cent alcoholic solution of picric acid.

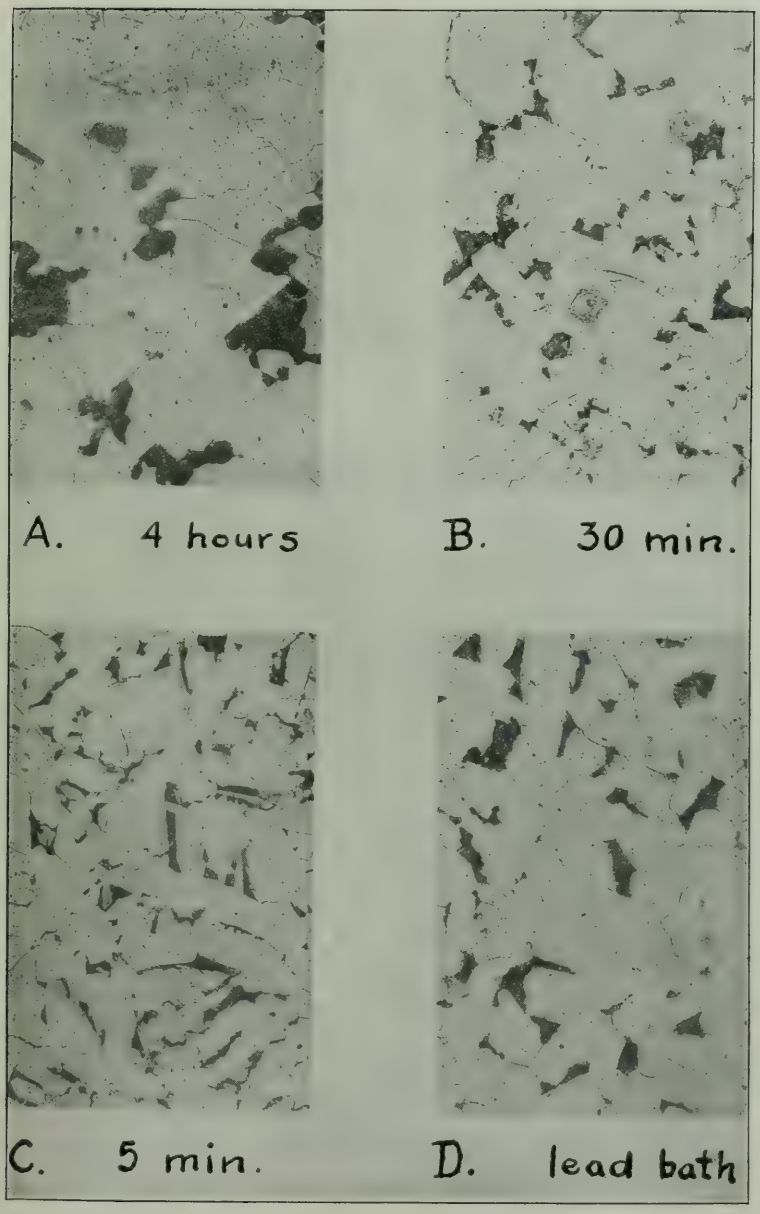

FIG. 3.—*Microstructure of low-carbon acid open-hearth steel containing 0.032 per cent phosphorus.* ×100

Heated to 900° C and cooled through 750–600° C range in the periods of time as indicated. Etching reagent, 5 per cent alcoholic solution of picric acid.

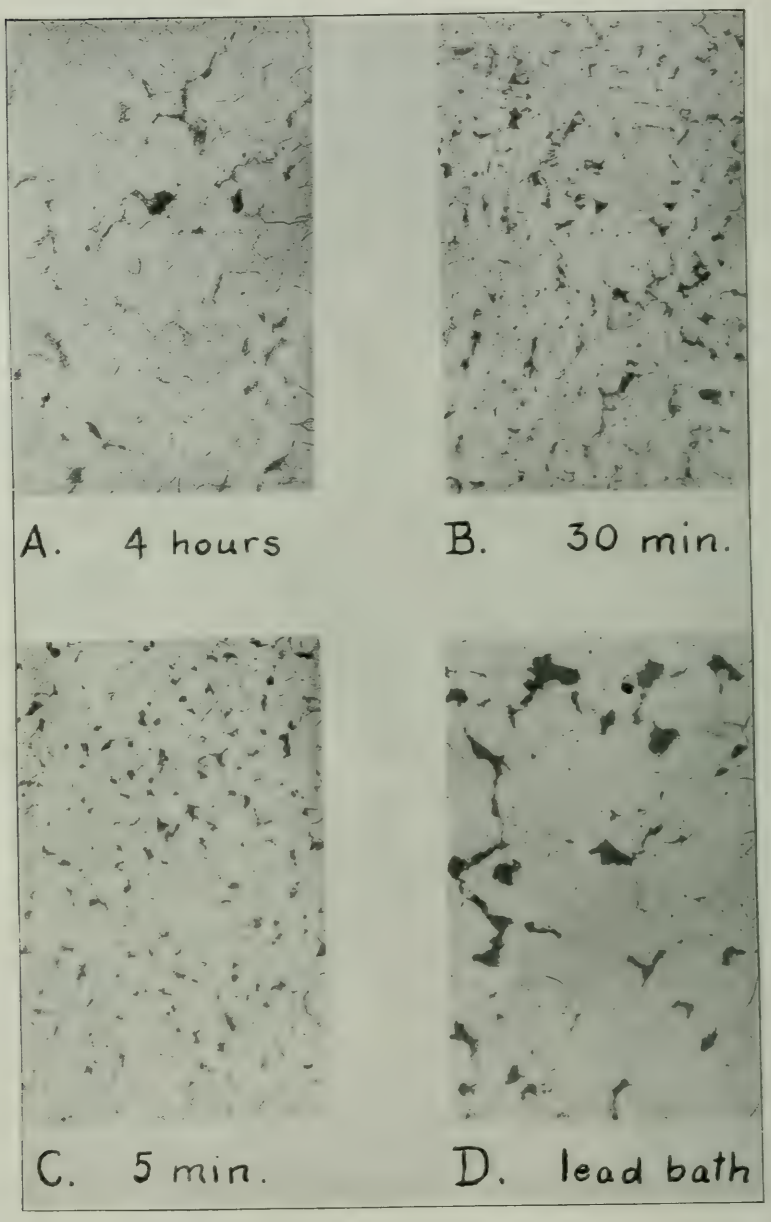

FIG. 3.—*Microstructure of low carbon basic open hearth steel containing 0.110 per cent phosphorus.* ×100

Heated to 925° C and cooled through 750–660° C range in the periods of time as indicated. Etching reagent, 5 per cent alcoholic solution of picric acid.

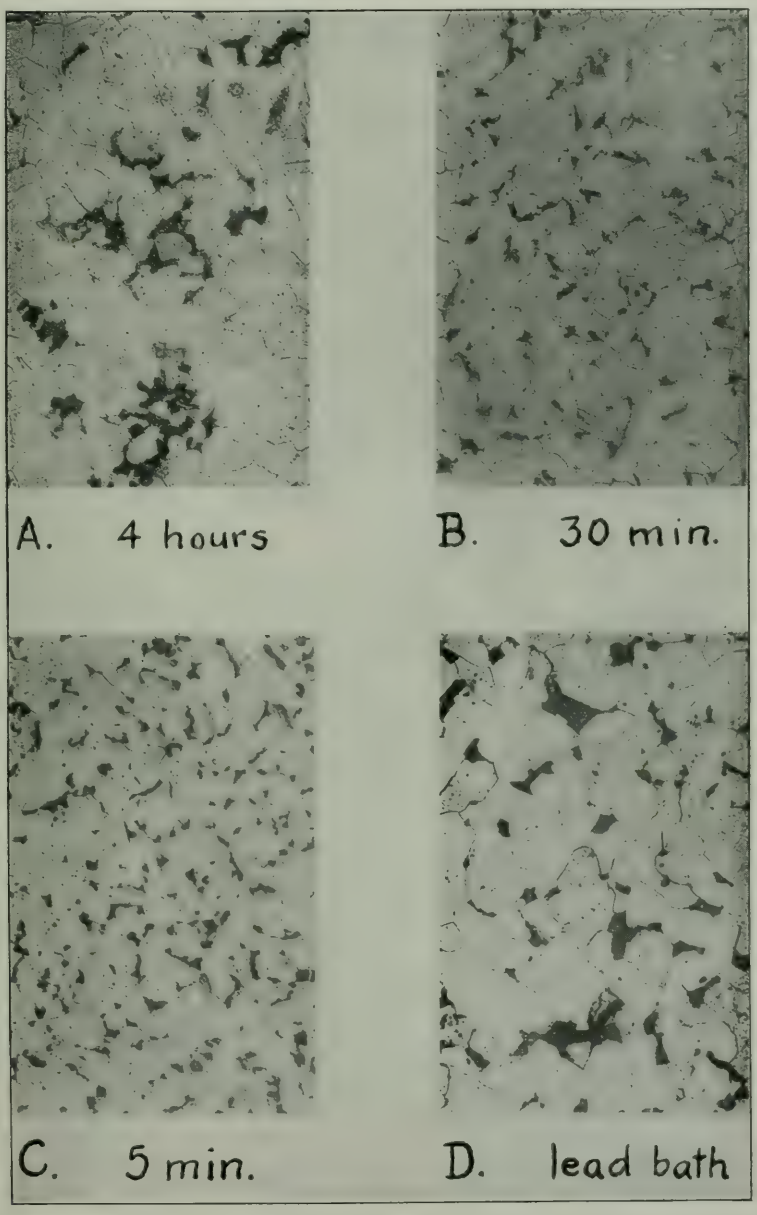

FIG. 5.—*Microstructure of low-carbon acid open-hearth steel containing 0.115 per cent phosphorus.* ×100

Heated to 900° C and cooled through 750–600° C range in the periods of time as indicated. Etching reagent, 5 per cent alcoholic solution of picric acid.

produced during the interval of time above the A_3 point occupied by the specimens in the course of the heat treatment. The data in the table given below are quite in agreement with what might be expected as to the relative grain size developed in the various specimens during the different periods of heating and cooling above the A_3 point (assuming Ac_3 for the two series of steels used in this investigation to be at 860° C) with the exception of the HT–7, lead-bath specimens, which show a marked increase in grain size even to a greater extent in all cases but one than in the case of the most slowly cooled series of specimens (HT–1, 4 hours). No satisfactory explanation can be offered as to the reason why the much shorter time of interval (33 minutes) above 860° C should develop an appreciably larger grain size in the HT–7, lead-bath specimens, than that developed in the specimens which were more slowly heated and cooled in the electric furnace (HT–1, 4 hours, and HT–4, 30 minutes).

Heat treatment (see Table 1)	Time of interval above 860° C	Average grain size in μ^2 (Table 2)			
		B. O. H. per cent P		A. O. H. per cent P	
		0.030	0.110	0.032	0.115
	Minutes				
HT-1, 4 hours	96	911	1075	3304	1161
HT-4, 30 minutes	50	767	1019	1728	924
HT-6, 5 minutes	26	589	714	1329	990
HT-7, 15 minutes (lead bath)	33	1736	2111	1682	1713

2. IRREGULARITY OF STRUCTURE

In several of the specimens there were found present in the structure large areas (amounting in extent to about 15 per cent of the area of the microscopic field) which were quite free from pearlite and had small to very large ferrite grains, as Figs. 6 and 7 will show. These carbonless areas appear to be due to the presence of a greater concentration of phosphorus, arising from nonuniformity in the distribution of the phosphorus in the steel which will be discussed in a later section of this article.

3. RELATION BETWEEN GRAIN SIZE AND PHOSPHORUS CONTENT

In Table 2 are given the results of the grain-size determination made of all the heat-treated specimens. The planimetric method of grain-size determination as modified and described by Jeffries[4]

[4] Z. Jeffries, Trans. Am. Inst. Min. Engrs., 54, p. 594; 1916. Also Met. and Chem. Eng., 18, p. 185; 1918.

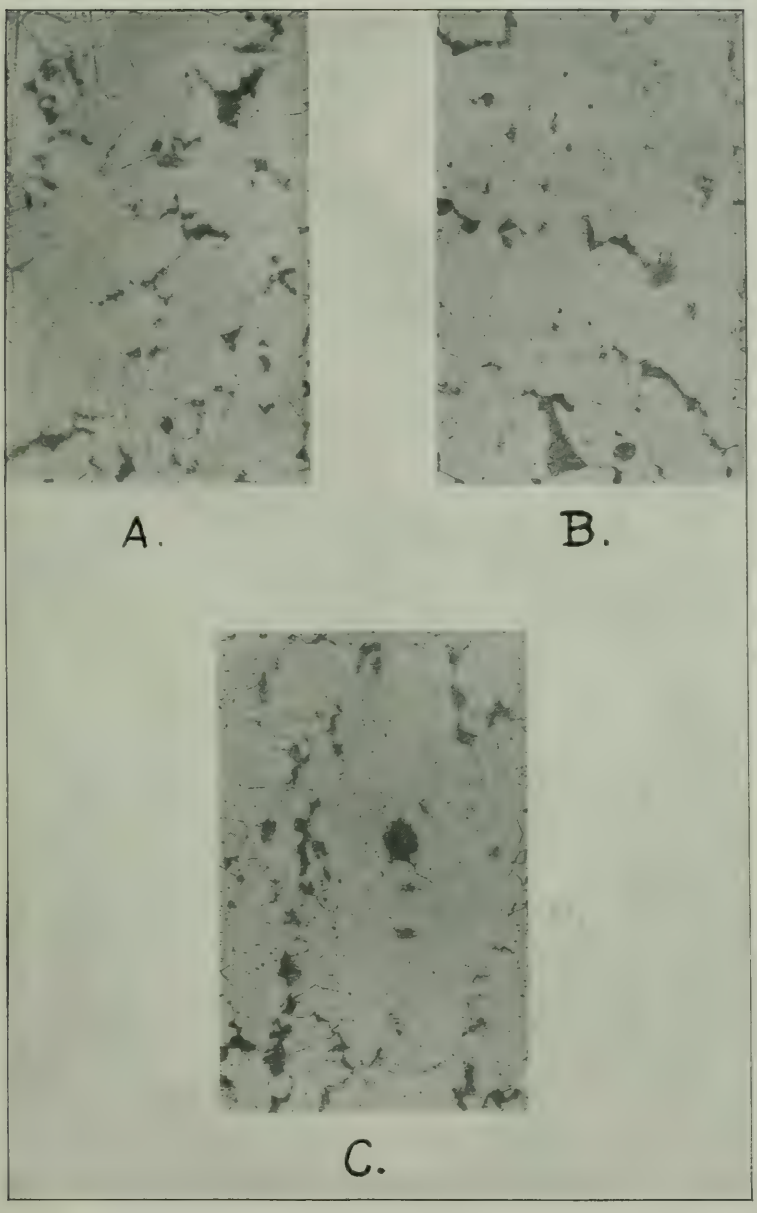

FIG. 6.—*Typical examples of irregularity in microstructure as found present in many of the specimens.* ×100

All the specimens were heated to 900° C and cooled through the 750–600° C range in the periods of time as indicated below. Etching reagent, 5 per cent alcoholic solution of picric acid. A—Low-carbon basic open-hearth steel containing 0.052 per cent phosphorus—30 minutes; B—Low-carbon basic open-hearth steel containing 0.110 per cent phosphorus—1 hour; C—Low-carbon acid open-hearth steel containing 0.115 per cent phosphorus—2 hours.

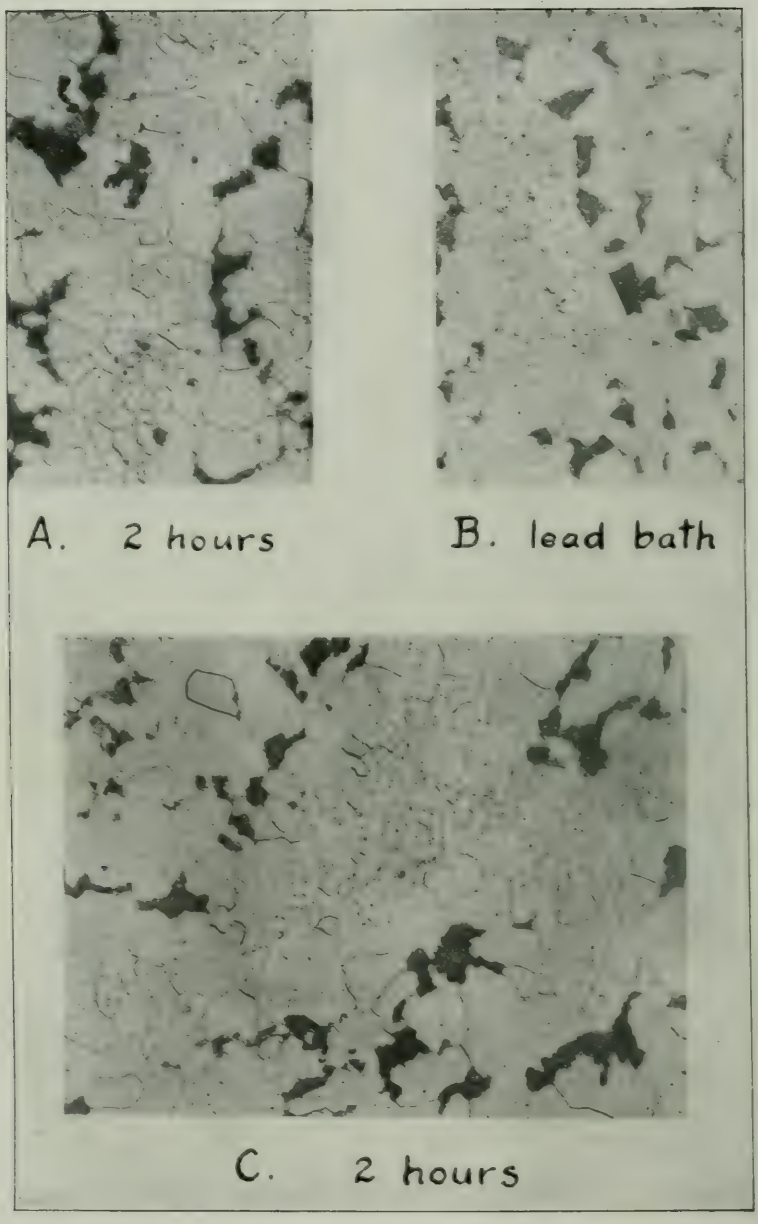

FIG. 7.—*Microstructure of low-carbon acid open-hearth steel containing 0.032 per cent phosphorus.* ×100

Heated to 900° C and cooled through 750–600° range in the periods of time as indicated. C is of the same specimen as A, but taken at a different spot. Shows carbonless areas as found in a few of the specimens, though particularly in specimens from this steel. Etching reagent, 5 per cent alcoholic solution of picric acid.

was followed. The pearlite kernels were counted together with the ferrite grains in determining the average area of the grains, the pearlite kernel being assumed as a grain. In comparing the average size of the pearlite kernels with that of the ferrite grains, the pearlite kernels appear, as estimated by the eye, to be about one-quarter in size of that of the ferrite grains for the quickly cooled sets of specimens (15 minutes and 5 minutes—B. O. H. and A. O. H.), one-half in size for some of the more slowly cooled sets (4 hours, 2 hours, 1 hour, 30 minutes, lead bath—B. O. H. and 30 minutes, lead bath—A. O. H.) and one-half to full size in the remaining slowly cooled sets (four hours, two hours, one hour—A. O. H.). The ratio of the number of ferrite grains to pearlite kernels (F:P) has also been determined, and the results are given in Table 2. There appears to be a well-defined and marked decrease in this ratio in the relatively quickly cooled specimens (15 minutes, 5 minutes, and lead bath) as compared with that prevailing for the more slowly cooled samples, and this is quite in accordance with what might be expected when one considers the opportunities the carbon has for being precipitated out of solid solution or austenite and the resulting pearlite masses to coalesce into larger masses during the cooling from 900° C, or above A_3, down through the transformation range. No relationship is seen to exist, however, between the ratio of ferrite grains to pearlite kernels (F:P) and the phosphorus content.

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TABLE 2.—Average Area of Grain Section of Ferrite and Pearlite, in μ^2

The pearlite kernels are included together with the ferrite grains in the grain count, and the ratio of ferrite grains to pearlite kernels (F:P) is given in the table below. Each value in this table is the average of three determinations made of each specimen, one at each corner of the quadrant-shaped specimen]

Phosphorus content, per cent	Grain section, when cooled through 750–600° C range in													
	4 hours		2 hours		1 hour		30 minutes		15 minutes		5 minutes		Lead bath, 15 minutes	
	Average grain area	F:P	Average grain area	F:P	Average grain area	F:P	Average grain area	F:P	Average grain area	F:P	Average grain area	F:P	Average grain area	F:P
B. O. H. 0.008	914	6.5	803	8.3	893	4.6	863	4.4	637	4.2	531	3.0	1683	2.5
B. O. H. 0.030	911	5.9	851	6.8	941	6.5	767	4.3	754	3.3	589	3.0	1736	4.2
B. O. H. 0.052	1103	6.4	1716	4.6	1080	5.3	1049	4.0	858	3.5	1137	4.4	1615	2.5
B. O. H. 0.080	806	8.7	768	8.8	1635	5.0	798	5.6	793	3.8	578	2.9	1803	2.8
B. O. H. 0.110	1075	10.6	948	9.5	976	5.4	1019	4.6	892	3.1	714	2.8	2111	3.6
A. O. H. 0.032	3304	5.8	2627	4.9	2230	2.6	1728	2.6	1532	2.0	1329	1.6	1682	3.6
A. O. H. 0.058	867	5.9	852	5.4	1328	5.6	704	4.7	778	2.7	830	2.4	1636	3.4
A. O. H. 0.085	1994	6.8	1814	5.0	1811	3.7	1052	4.1	1017	2.5	1384	1.8	1757	2.8
A. O. H. 0.115	1161	7.7	1154	5.7	1635	3.9	924	4.3	1029	2.7	990	2.0	1713	2.8

Because of the irregularity in the grain-size results, which was evidently due to the nonuniform distribution of the phosphorus in the steels, no definite conclusions could be drawn as to the relationship between the grain size and phosphorus content and also the effect of various rates of heating and cooling followed in the series of heat treatments.

4. EFFECT OF RATE OF COOLING UPON THE PEARLITIC STRUCTURE

With respect to the effect of the rate of cooling through the 750 to 600° C range, the divorcing of pearlite had progressed to some extent in the more slowly cooled specimens (4 hours, 2 hours, 1 hour, and 30 minutes, especially in the steels with higher phosphorus content) and this divorcing and the coalescing of the liberated cementite appear to have been more pronounced in the B. O. H. steel specimens than in the A. O. H. ones. However, there appears to be no well-defined relation between the degree of divorcing developed and the phosphorus content, within the limits 0.008 to 0.115 per cent phosphorus.

The undivorced pearlite was found to be mainly in the sorbitic and sublamellar [5] conditions for both B. O. H. and A. O. H. series of specimens, though in the more slowly cooled specimens (four hours, two hours, and one hour) there was a considerable quantity of fine lamellar pearlite present.

V. HARDNESS

1. EXPERIMENTAL DATA

Both the Shore and Brinell hardness values were determined, and the results are given in Table 3. In the Brinell test the specimens were too small and thin to permit the use of a 3000 kg load without distortion arising from the indentation of the specimen, so a 500 kg load was used instead with entire satisfaction.

2. ANALYSIS OF RESULTS

(*a*) SHORE.—The results, which are rather irregular, show no well-defined relation between the hardness and the phosphorus content and also the rate of cooling through the 750 to 600° C range. The range between the minimum and maximum individual values was 12.0 to 21.0 = 9.0, and 70 per cent of the individual values lay between the limits 17.0 and 19.0.

[5] H. M. Howe and A. G. Levy, "Notes on pearlite," Jour. Iron and Steel Inst., **94**, p. 220; 1916, II.

TABLE 3.—Brinell and Scleroscope Hardness

[Brinell: 500 kg load applied for 30 seconds, using a 10 mm diameter ball. Shore: Self-registering scleroscope with universal hammer. Average of seven determinations for each specimen]

Phosphorus content, per cent	Hardness for specimens cooled through 750–600° C range for—													
	4 hours		2 hours		1 hour		30 minutes		15 minutes		5 minutes		Lead bath, 15 minutes	
	Brinell	Shore	Brinell	Shore	Brinell	Shore	Brinell	Shore	Brinell	Shore	Brinell	Shore	Brinell	Shore
B. O. H. 0.008	56	17.9	55	18.0	56	18.6	59	19.1	58	17.4	61	18.9	60	18.6
B. O. H. 0.030	58	17.1	61	16.8	[a]65	18.5	63	19.1	62	17.5	65	19.1	63	15.8
B. O. H. 0.052	64	14.9	65	16.6	61	18.1	68	18.1	64	17.4	62	16.9	68	14.8
B. O. H. 0.080	65	16.5	68	16.8	67	17.2	67	17.8	70	18.0	68	18.7	73	17.3
B. O. H. 0.110	63	17.9	65	18.5	70	17.9	67	20.3	68	18.6	72	19.1	73	17.5
A. O. H. 0.032	60	16.4	69	17.2	63	17.1	68	16.3	68	17.9	69	18.4	70	17.8
A. O. H. 0.058	69	17.1	69	18.1	73	17.7	73	18.9	74	17.3	67	19.3	74	18.1
A. O. H. 0.085	70	18.9	70	18.0	68	18.8	74	19.4	74	18.8	73	19.0	73	19.3
A. O. H. 0.115	74	18.3	65	17.1	72	17.4	73	18.3	73	17.9	74	18.8	73	17.6

[a] Load of 3000 kg used (specimen too small to prevent distortion at this load)

(*b*) BRINELL.—A more satisfactory relationship was obtained between the hardness and phosphorus content. In all of the seven differently heated sets of specimens there is a small but definite increase in hardness, as the phosphorus content is raised from 0.008 to 0.080 per cent in the B. O. H. series, though the hardness remains practically stationary as the phosphorus content is increased to 0.110 per cent, excepting in the one hour and five minute sets, where the increase in hardness continues. In the A. O. H. series the results are rather erratic, though in a general way the hardness increases a little as the phosphorus content is increased from 0.032 to 0.058 per cent and then remains practically stationary as the phosphorus is increased to 0.115 per cent. In the four-hour set the increase in hardness is practically continuous as the phosphorus content is increased from 0.032 to 0.115 per cent. In most of the sets of heat-treated specimens, both B. O. H. and A. O. H., the increase in hardness is quite in agreement with the rate of increase as indicated in the statement by Stead [6] that the Brinell hardness of saturated solid solution of iron phosphide in iron increases with the phosphorus content by about 1.3 points for each 0.01 per cent phosphorus. D'Amico [7] reports an increase of hardness by about 12 Brinell hardness numbers for each 0.1 per cent phosphorus.

No well-defined relationship could be established between the hardness and the rate of cooling through the 750 to 600° C range, though the more slowly cooled specimens (four hours, two hours, and one hour, B. O. H. and A. O. H.) were, in general, a little softer than the more quickly cooled ones.

VI. DISTRIBUTION OF PHOSPHORUS

1. STEELS WITH LOWER PHOSPHORUS CONTENT

As stated in Section IV (2), there were met with, during the microscopic examination of the entire series of specimens prepared for this investigation, a number of specimens in which large carbonless or free from pearlite areas and abnormally large ferrite grains were found present in portions of the microsection. These irregularities in structure were attributed to a nonuniform distribution of the phosphorus, there being a greater concentration of this element present in these carbonless and

[6] Stead, "Some of the ternary alloys of iron, carbon, and phosphorus," Jour. Soc. Chem. Ind., 33, p. 174; 1914.

[7] See footnote 2

large ferrite-grains areas than in the surrounding metal. In addition, in several of these large carbonless areas there was noticed an unusual structure distributed throughout the cluster of ferrite grains and which appeared to stand out in relief as viewed through the microscope using vertical illumination.[8] This structure may be seen in Figs. 8, *a*, and 9, *d*, and it was clearly seen when the rest of the microscopic field was in focus. On closer examination this relief structure was found to form a part of a network and mesh system of markings, very suggestive of a cellular structure, distributed over the rest of the microsection, though the throwing a little out of focus of the microscopic field was necessitated in order to bring out clearly this system of markings, as Fig. 8, *b*, *c*, and Fig. 9, *a*, *b*, *c* will illustrate. The network stood out as light-colored markings and the meshes appeared as of a darker color, while a reversal of the focusing slightly beyond the point of sharp focus and in a direction toward the specimen gave the opposite color effect, though the contrast between the light and dark portions was less pronounced.[9] The cell walls of this network appear to cross the grain boundaries of the ferrite grains in places, thus indicating the presence of two distinct systems of etching patterns, the usual ferrite and pearlite system and the cellularlike system, the latter apparently being independent of and superposed on the former. This cellularlike structure was not developed in the case of the 0.008 and 0.030 per cent phosphorus B. O. H. steels even after fairly prolonged etching (20 to 25 minutes with 5 per cent alcoholic picric acid and 30 seconds with 2 per cent alcoholic nitric acid), though it was readily brought out in the

[8] The author's attention was called, subsequent to the preparation of this paper, to G. F. Comstock's article "Microstructure of annealed soft steels, with special reference to phosphorus in tin plate," published in Forging and Heat Treatment, **7**, pp. 60–63, Jan., 1921, in which he reports the presence of faint relief markings in the ferrite areas comprising the "ghost streaks" in specimens of steel sheet bar containing 0.11 per cent carbon and 0.075 per cent phosphorus that had been annealed for four hours at 800 and 850° C., or within the Ac_1 to Ac_3 range, though this unusual structure was not shown as being present in specimens of the same steel annealed at 900° C. and at higher temperatures. On etching with Stead's reagent portions of this relief structure were darkened while the rest of the ferrite remained bright, thus indicating that phosphorus was responsible for this peculiar structure. Although it is true that the specimens used in this investigation were heated to 900° C, it would seem from the fact that the cellularlike structure persisted in many of the specimens examined that the time of heating to and above Ac_3 was not long enough to produce a complete diffusion of the phosphorus and consequent elimination of the relief or cellularlike structure. No attempt was made, however, to investigate this point fully, though the cellularlike structure was found to be more pronounced in the rapidly cooled specimens than in the slowly cooled ones.

[9] This color contrast as occasioned by the unequal depth of etching produced is in agreement with F. Osmond's observation, as stated on p. 17 of his Microscopic Analysis of Metals, edited by J. E. Stead and published by Charles Griffin & Co. (Ltd.), London, 1904, that cementite particles assume a dark color as contradistinguished with the light-colored ferrite background when the focusing of the microscope is carried toward the specimen and not quite to the point of focus. The network of the above-described cellularlike structure represents the portion of the metal which is lower in phosphorus content, as will be shown in a later section, and hence has been eaten away to a greater extent by the etching medium than the adjoining higher-phosphorus portions which stand out in relief.

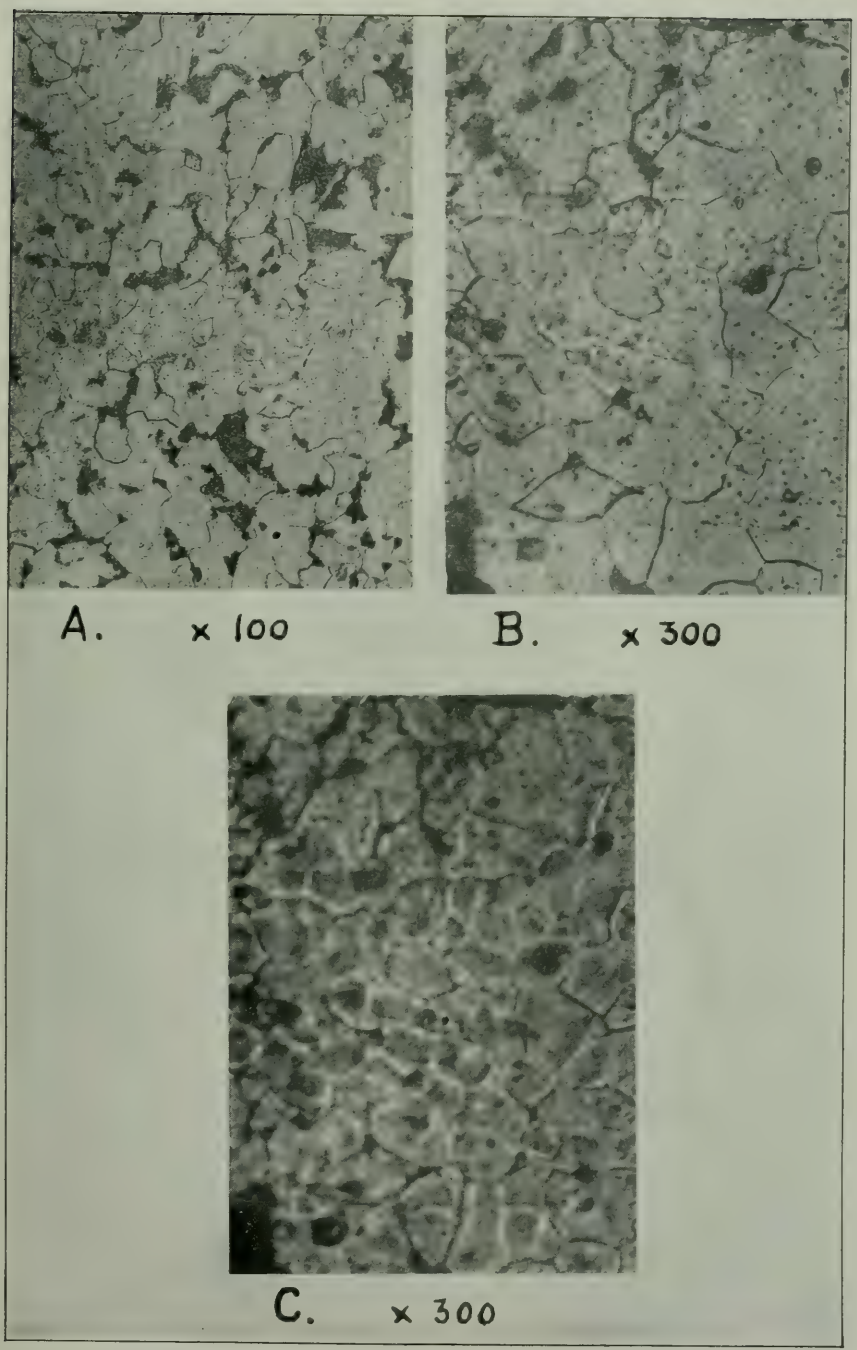

FIG. 8.—*Cellularlike structure in low-carbon acid open-hearth steel containing 0.032 per cent phosphorus*

Heated to 900° C and cooled through 750–600° C in 15 minutes. B was taken near center of field shown in A, and field is in sharp focus. C is same field as in B, but thrown a little out of focus to bring out cellularlike structure. Etching reagent, 5 per cent alcoholic solution of picric acid.

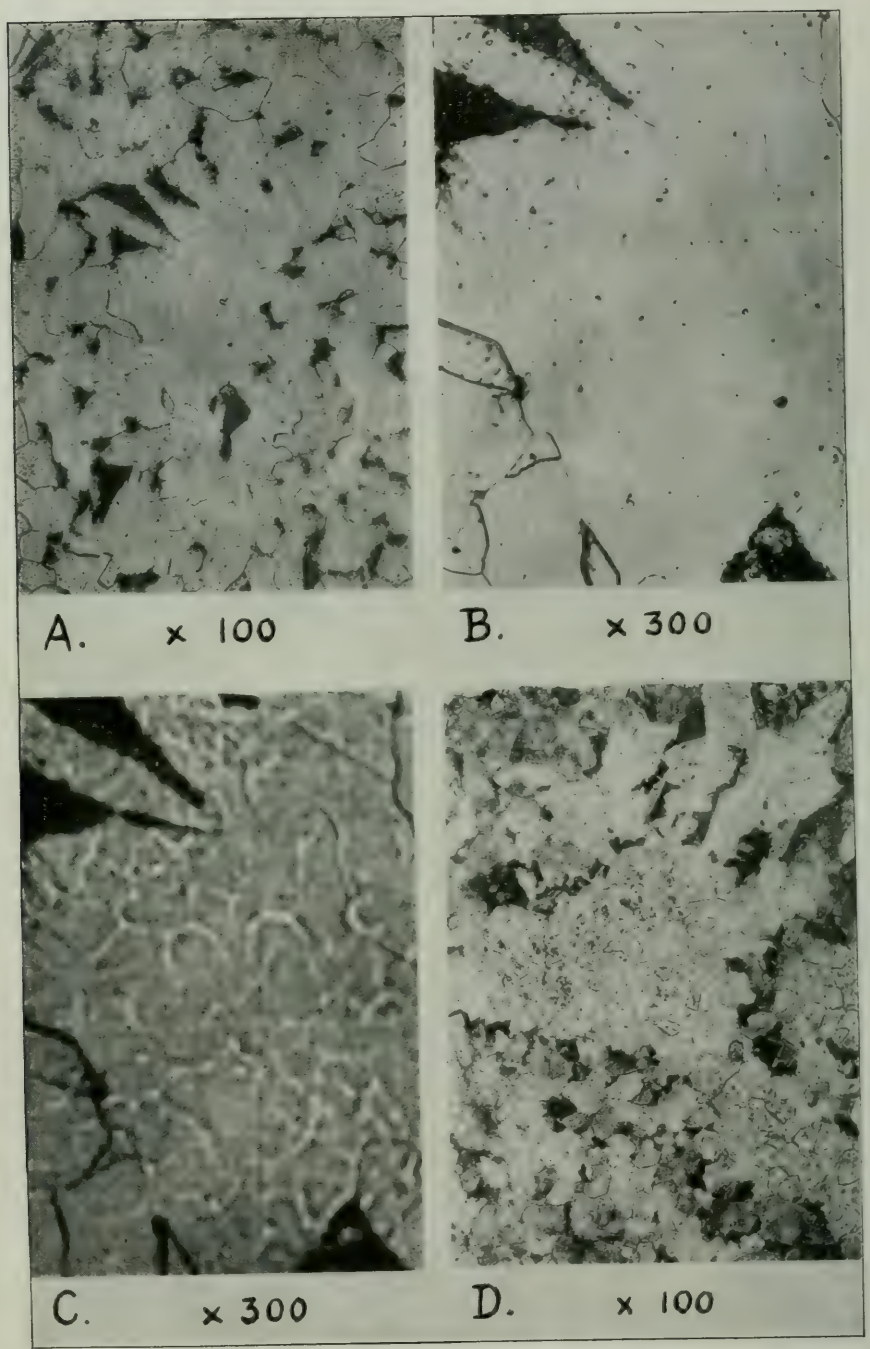

FIG. 9.—*Cellularlike structure in same specimen shown in Fig. 8 but at a different portion of microsection*

B was taken at center of field shown in A, and the field is in sharp focus. C is the same field as in B, but thrown a little out of focus to bring out cellularlike structure. D was taken at another spot in same microsection. Etching reagent, 5 per cent alcoholic solution of picric acid; D was also etched with Stead's reagent following the picric acid etching.

0.032 per cent phosphorus A. O. H. steel and in the other steels, both B. O. H. and A. O. H., containing the higher percentages of phosphorus. This fact suggests that the cellularlike structure will not be developed unless the phosphorus content of the steel be greater than about 0.01 or 0.02 per cent.

In order to prove that the carbonless areas, large ferrite grains, and cellularlike structure were due to the phosphorus, etching with alcoholic cupric chloride solution acidified with hydrochloric acid (Stead's reagent), which was found by trial to give more satisfactory results than several of the usual reagents recommended for the detection of phosphorus segregation such as Heyn's reagent, Rosenhain and Haughton's reagent, Stead's aqueous solution of picric acid, and heat tinting, was tried following the etching with picric acid or nitric acid. It is well known that through the action of Stead's reagent the portions of the etched surface low in phosphorus content have a layer of metallic copper or a brown-colored layer deposited thereon while the portions richer in phosphorus remain colorless or nearly so because of the greater resistance to the action of the etching.[10, 11, 12] As to the nature of the brown-colored deposit, Rawdon[13] states that this coloration or tint, attributed by Stead to a much-retarded deposition of copper, as represented by the darkened surface layer when dissolved off from the etched specimen gave a faint yet clear test for copper. In no case where etching with Stead's reagent was used in this work was there any metallic deposit of copper formed on the specimens.

Fig. 9, *d*, and Fig. 10, *a*, *b*, *c*, are typical of the results obtained by etching with Stead's reagent. It will be noted that the large carbonless areas and large individual ferrite grains remain practically colorless while the surrounding areas assume a mottled appearance, which on closer examination and at higher magnification was seen to possess a similar though less pronounced etch pattern as that developed in the 0.42 per cent phosphorus steel specimens described in the next subsection. However, in the case of the lower phosphorus steels (0.008 and 0.030 per cent phosphorus B. O. H.) the etch pattern was not very pronounced or definite, evidently because of the insufficient amount of phosphorus present.

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[10] Stead, "Some of the ternary alloys of iron, carbon, and phosphorus," Jour. Soc. Chem. Ind., **33**, p. 174, 1914; seventh section of Part I; also Jour. Iron and Steel Inst., **91**, p. 174, 1915, I.

[11] Rawdon, "Some unusual features in the microstructure of wrought iron," Trans. Amer. Inst. Mining Engrs., **588**, p. 501, 1918; also B. S. Technologic Paper No. 97.

[12] Whiteley, "The distribution of phosphorus in steel between the points Ac_1 and Ac_3," Jour. Iron and Steel Inst., **101**, pp. 363 and 370–372; 1920, I.

[13] See footnote 11.

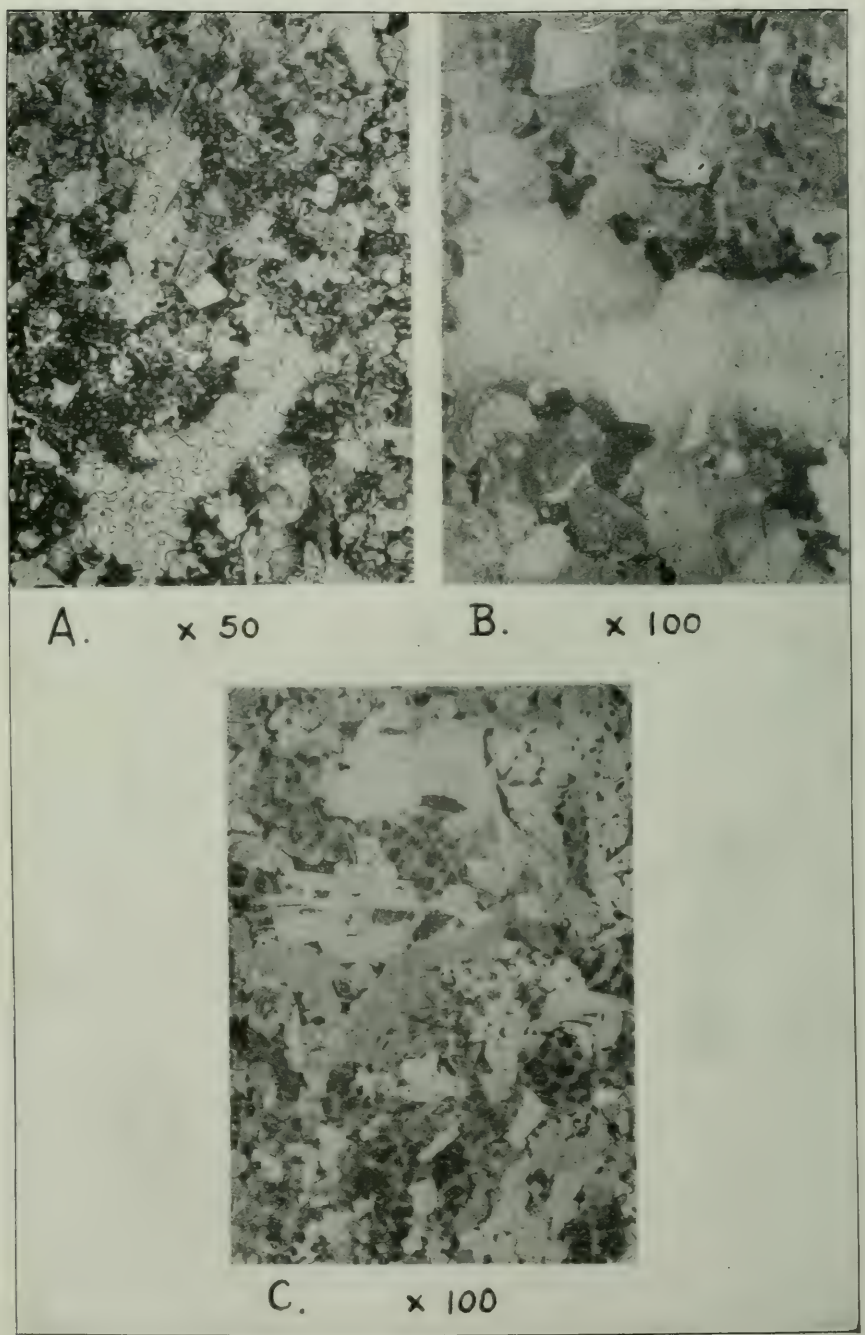

FIG. 10.—*Carbonless areas and large ferrite grains in low-carbon acid open-hearth steel, as brought out by etching with Stead's reagent*

The specimen represented by A and B contained 0.032 per cent phosphorus, and was heated to 900° C and cooled through 750–600° C range in 2 hours. The specimen represented by C contained 0.058 per cent phosphorus, and was heated to 900° C and cooled through 750–600° range in 5 minutes. B was taken in the same microsection as A but at a different spot. Etching reagent, 5 per cent alcoholic solution of picric acid followed by Stead's reagent.

2. STEELS WITH HIGHER PHOSPHORUS CONTENT

For the purpose of determining whether or not a similar and more pronounced cellularlike structure as developed by etching with either picric or nitric acid and etching pattern as formed by Stead's reagent would be obtained in steels of higher phosphorus content, a series of specimens cut from a three-fourths-inch round of the following composition: 0.34 per cent carbon, 0.42 per cent phosphorus, 0.10 per cent silicon, 0.11 per cent manganese, and 0.029 per cent sulphur that had in connection with another investigation been heated to both 900 and 800° C and cooled through the 800 to 650° C range at various rates (two hours, one hour, accelerated furnace cooled, and air cooled) were studied.

A cellularlike structure similar to that found in the lower phosphorus steels was found present in the two-hour and one-hour cooled specimens of both the 900 and 800° C heatings (see Fig. 11 and Fig. 12, *a*, *b*) and in the accelerated furnace-cooled and air-cooled specimens of the 800° C heating, though in these last two specimens this cellularlike structure was quite clearly seen only at higher magnification because of the much finer granular structure (ferrite and pearlite) developed by the quicker rates of cooling. It should be noted that this cellularlike structure is absent in different spots where there is a cluster of more or less large pearlite kernels, and this is apparently due to a lower phosphorus content occasioned by the repellant action which carbon dissolved in iron is known to exert upon phosphorus. This assumption appears to be borne out in Fig. 13, *b*, and Fig. 15, *c*, where the areas surrounding the pearlite kernels have been deeply tinted by Stead's reagent, thus indicating a lower phosphorus content in these regions.

As for the results obtained by etching with Stead's reagent, Fig. 13, *a*, *c* show the general manner of distribution of the phosphorus as found in the two-hour and one-hour cooled specimens, the uncolored or light portions being richer in phosphorus than the dark portions. Figs. 12, *c*, and 13, *b* show in greater detail the arrangement of the low (dark) and high phosphorus (light) areas. The phosphorus-rich areas shown in Fig. 13, *a*, *c* appear to be the originally landlocked portions that had formed between the dendrites of purer iron or primary crystallites during the solidification of the metal, though the dendritic structure is not very marked evidently because of the working given the metal during its fabrication into three-fourths-inch rounds. It appears

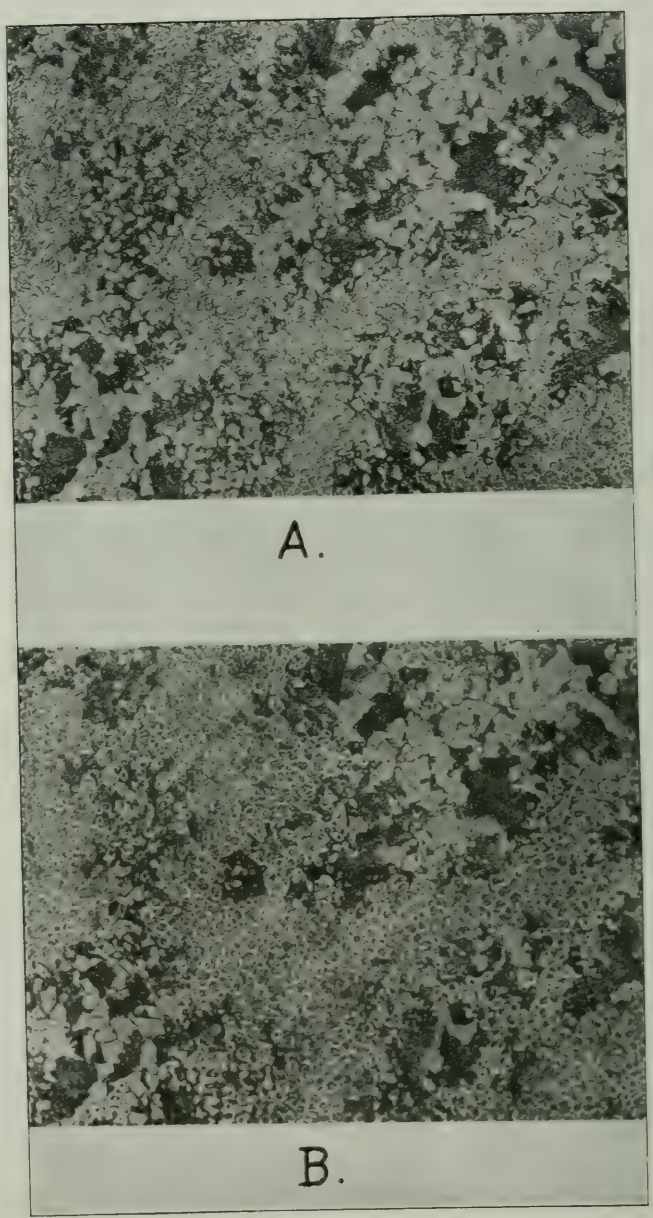

FIG. 11.—*Cellularlike structure in medium carbon steel containing 0.42 per cent phosphorus.* ×100

Heated to 900° C and cooled through 800–650° C range in 1 hour. B is same field as shown in A, but thrown a little out of focus. Etching reagent, 5 per cent alcoholic solution of picric acid.

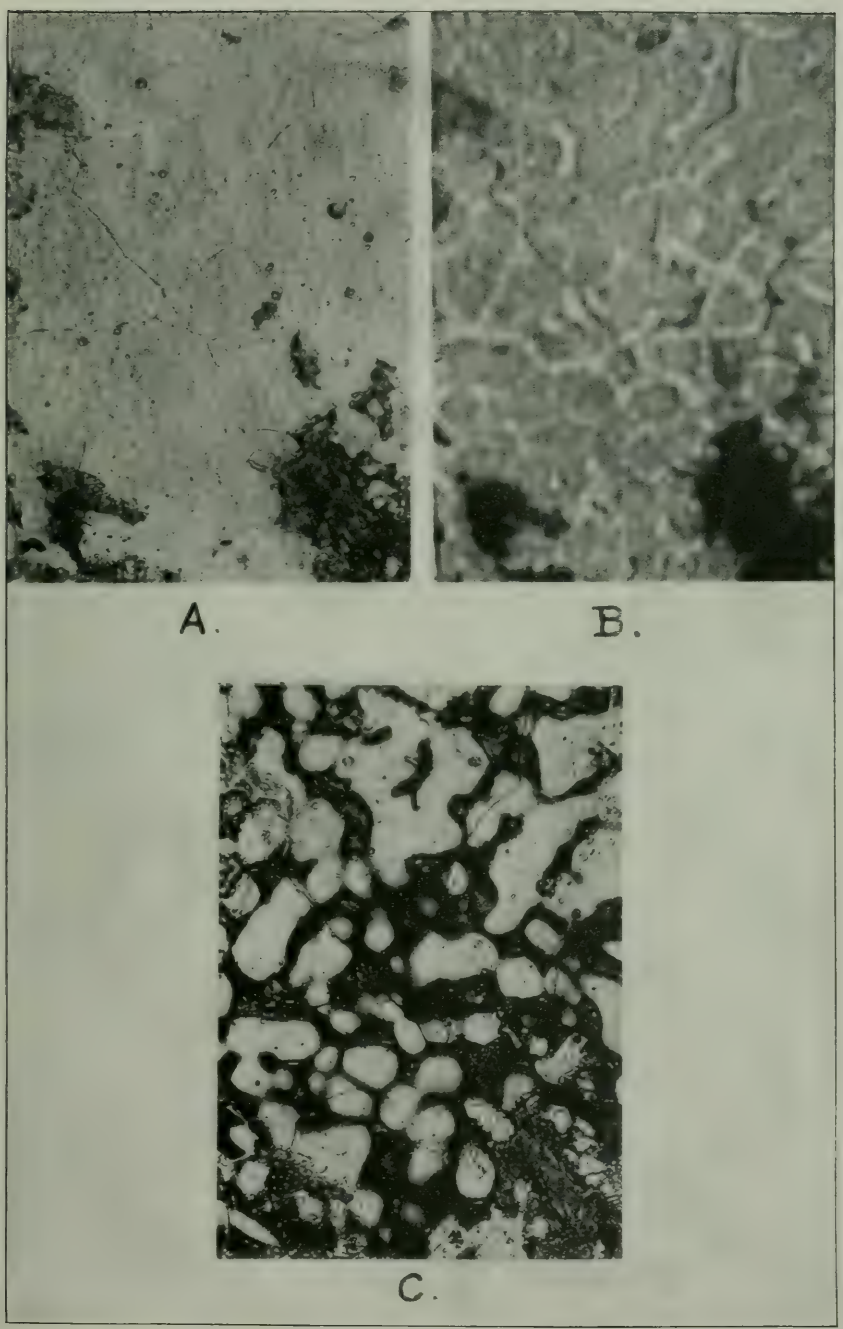

FIG. 12.—*Cellularlike structure in medium carbon steel containing 0.42 per cent phosphorus, before and after etching with Stead's reagent.* ×500

Same specimen as in Fig. 11, but taken at different portion of microsection. A, B, and C are of the same field, but B has been thrown a little out of focus. Etching reagent, 5 per cent alcoholic solution of picric acid; C was etched with Stead's reagent following the picric acid etching.

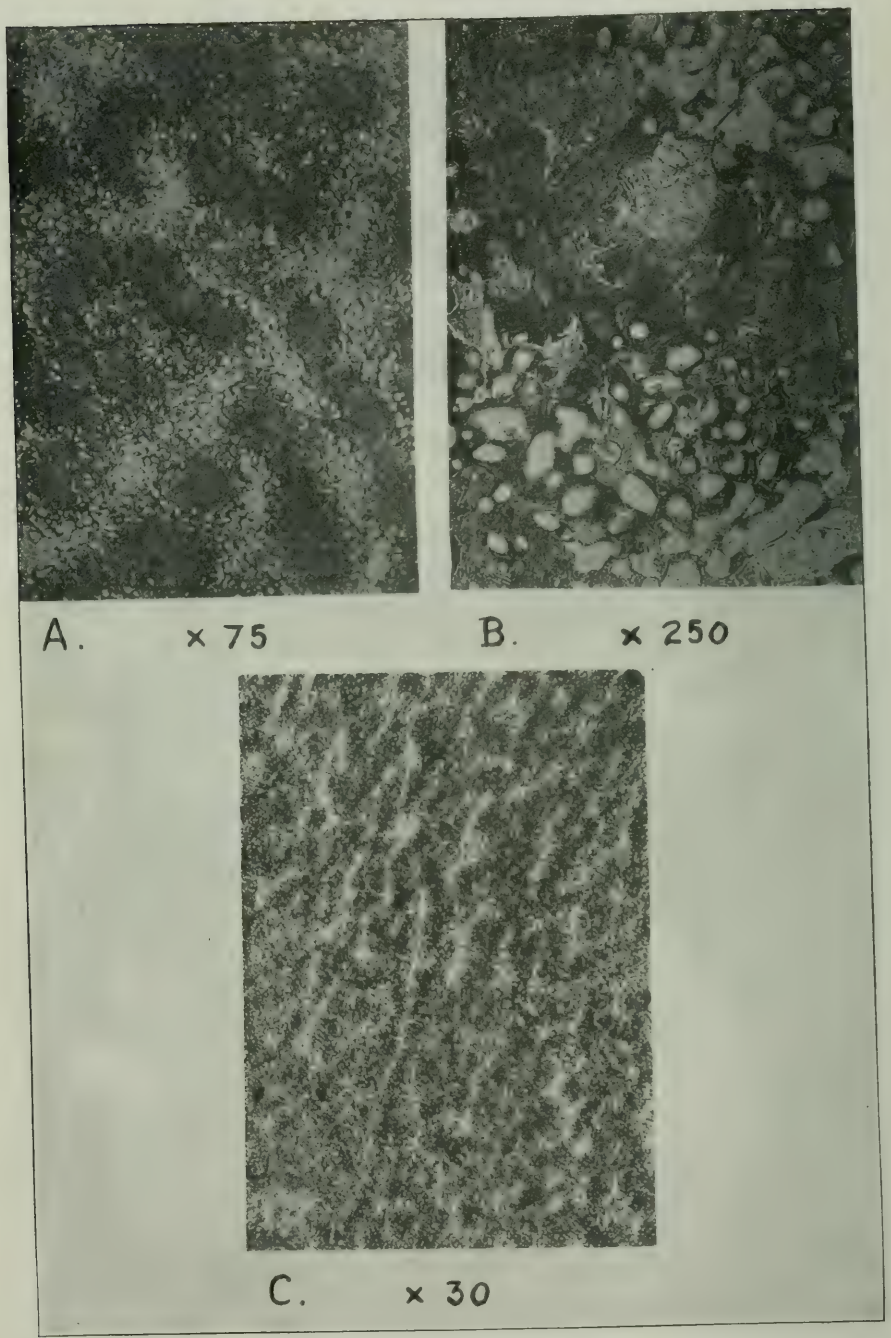

FIG. 13.—*Distribution of phosphorus (light areas) in medium carbon steel containing 0.42 per cent phosphorus, as revealed by etching with Stead's reagent*

The specimen represented by A and B was heated to 900° C and cooled through the 800–650° C range in 1 hour (same specimen as in Figs. 11 and 12), and that by C was heated to 900° C and cooled through 800–650° C range in 2 hours. B was taken at center of field shown in A. Etching reagents: A and B, 5 per cent alcoholic solution of picric acid followed by Stead's reagent; C, 2 per cent alcoholic solution of nitric acid followed by Stead's reagent.

probable that after the solidification had been completed the carbon diffused into the purer portions or the dendritic spines, leaving the other impurities as phosphorus and sulphur in the less pure portions or the landlocked areas as may be well illustrated in Fig. 7, *c*, where the carbon in the form of pearlite lies outside of a good-sized zone free from pearlite and containing numerous inclusions of manganese sulphide (cross-sectional view of the 1-inch round).

In the accelerated furnace-cooled and air-cooled specimens of the 900° C heating the phosphorus was found to be distributed in a different manner, as indicated in Fig. 14, *a*, and the phosphorus-rich portions (phosphoferrite or a solution of iron phosphide in iron) to be in the form of small acicular and globular-shaped masses grouped together in clusters, as shown in Figs. 14, *b*, *c* and 15, *c*. Fig. 15, *a*, *b* cover the same field as that in Fig. 15, *c*, but show the microsection as etched with nitric acid alone, thus revealing a light-colored etching pattern which corresponds exactly with the dark or low phosphorus portions of the etch pattern in Fig. 15, *c*.

It will also be noticed that the light-colored cell walls of the cellularlike structure in Fig. 12, *b* correspond exactly in position with and overlap the dark-colored etch-pattern in Fig. 12, *c*, though the latter is, in general, of greater width along the various cell walls. The light-colored network and dark-colored etch pattern are seen to cross the ferrite grain junctions in many places, and a similar tendency may be found in Fig. 13, *b*, thus confirming the statement made above (Sec. VI, 1) that the cellularlike structure appears to be independent of the ferrite and pearlite structure.

Fig. 14, *c* shows the structure of the 900° C air-cooled specimen, which had been heat tinted to a good blue color. The light-colored, phosphorus-rich portions stand out in good relief against the dark oxidized surface of the surrounding and poorer in phosphorus metal, and appear to be quite similar in general formation to that prevailing in the 900° C accelerated furnace-cooled specimen (Fig. 14, *b*). It may be of interest to note here Whiteley's statement[14] that areas containing as much as 0.6 per cent phosphorus are readily detected by heat tinting.

[14] Loc. cit. (see footnote 12), p. 375.

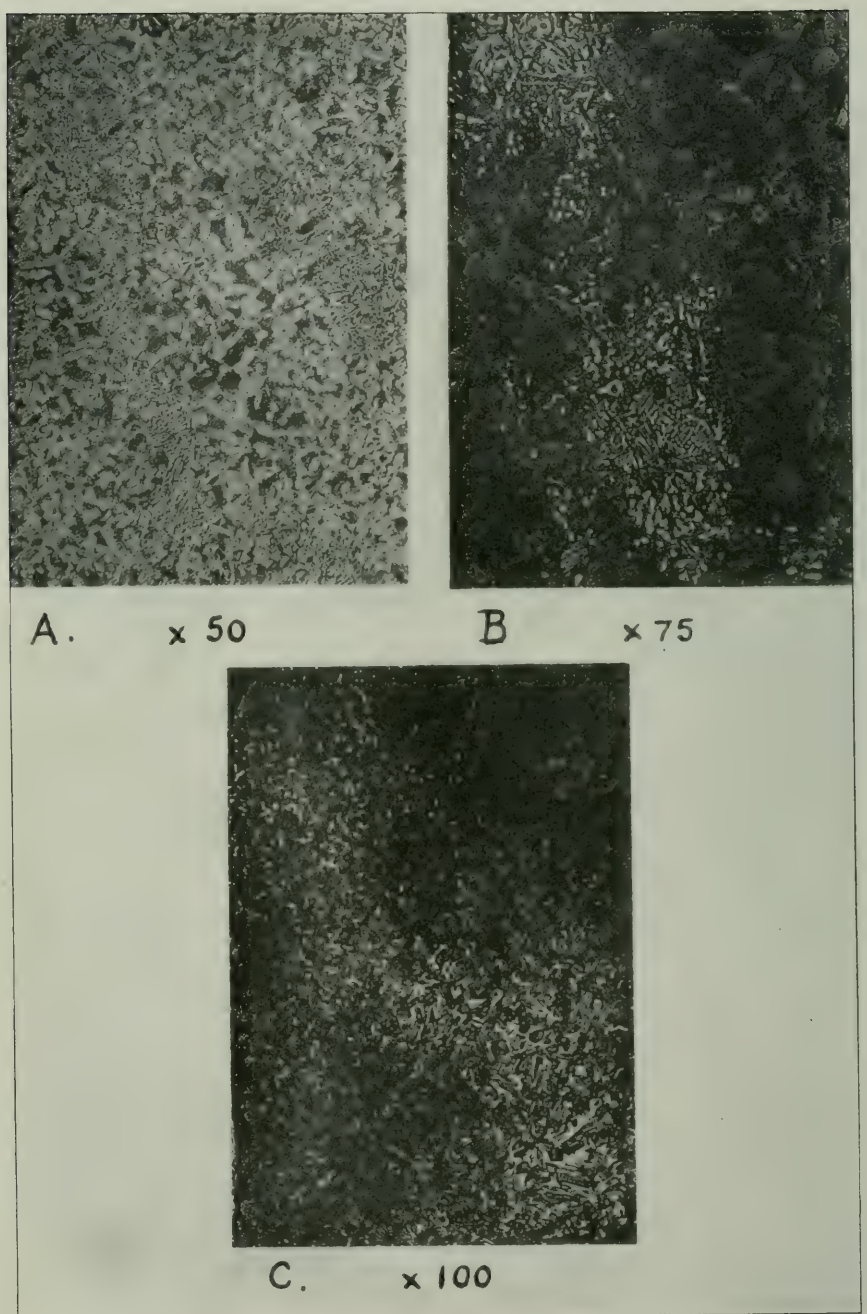

FIG. 14.—*Distribution of phosphorus in medium carbon steel containing 0.12 per cent phosphorus*

The specimen represented by A and B was heated to 900° C and cooled quickly in the furnace, and that by C was heated to 900° C and air-cooled. Etching reagents: A, 2 per cent alcoholic solution of nitric acid; B, Stead's reagent; C, heat-tinted in molten lead bath at 300° C to good blue color.

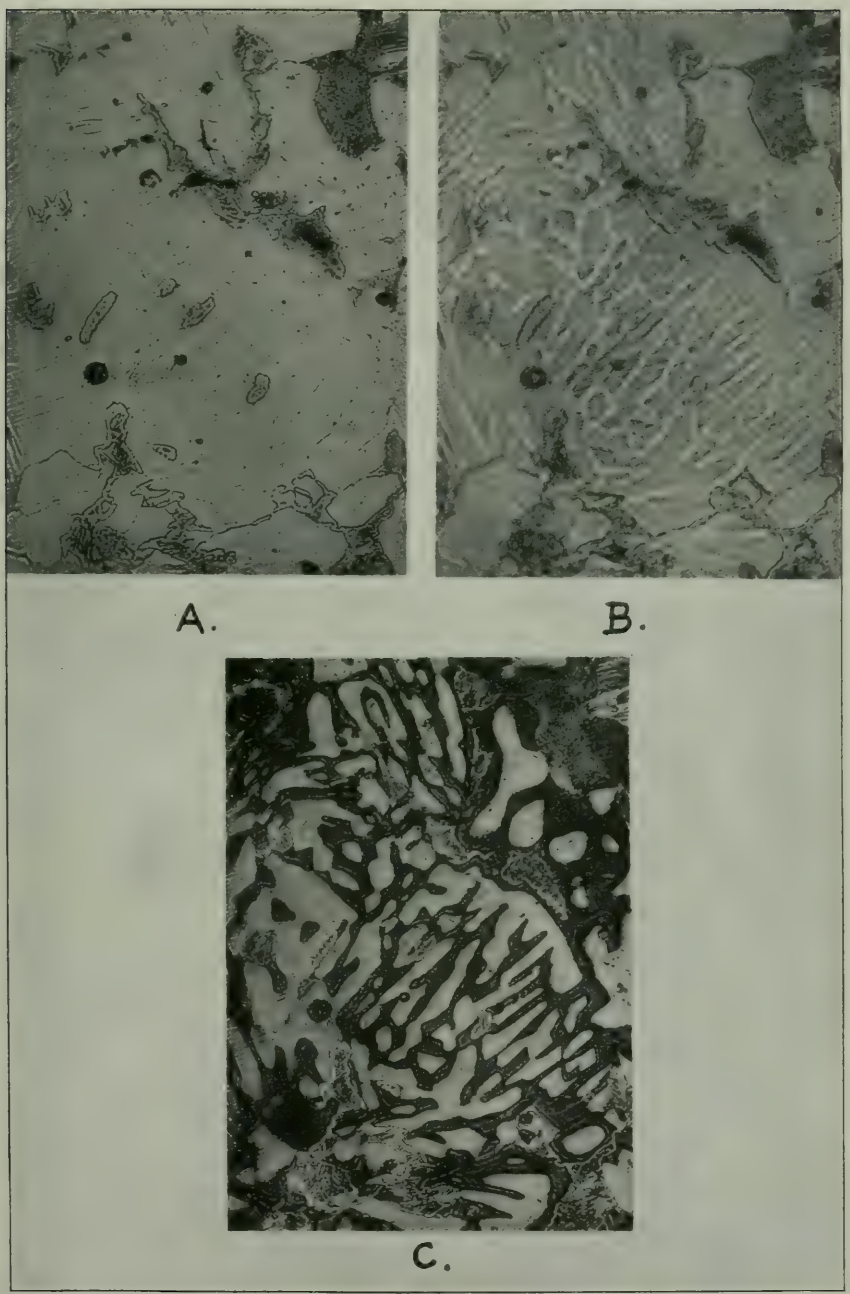

FIG. 15.—*Phosphorus-rich area shown in Fig. 14 (B), before and after etching with Stead's reagent.* ×500

A, B, and C are of the same field, which was taken at center of the cluster of uncolored spots shown in lower half of Fig. 14 (B), though B has been thrown a little out of focus. Etching reagent, 2 per cent alcoholic solution of nitric acid; C was etched with Stead's reagent following the nitric-acid etching.

3. INTERPRETATION OF RESULTS

It must be evident from the fact that the etch pattern as developed by Stead's reagent corresponds exactly in position with and overlaps the cellularlike structure as developed by picric or nitric acid etching that both systems of etch patterns are due to one and the same cause, the presence of phosphorus. This element is found to be more concentrated in the meshes of both etch patterns, these meshes appearing as dark areas in the cellularlike structure and as light areas in the etch pattern produced by Stead's reagent. This conclusion appears to be further borne out by the following considerations:

(*a*) Both the cellularlike structure and Stead's reagent etch pattern are more pronounced in the higher phosphorus steels than in the lower phosphorus steels.

(*b*) The large uncolored areas or meshes of the Stead's reagent etch pattern tend to be further away than nearer to the pearlite kernels or clusters of pearlite kernels in the 0.42 per cent phosphorus steel specimens, and a similar tendency has been observed to be present in the lower phosphorus steels, though in a less striking manner. This phenomenon is attributed to the repellant action of carbon upon phosphorus when in solution in the iron.

(*c*) In Figs. 13, *b* and 15, *c* it will be noted that the cementite laminæ of the pearlite kernels remain uncolored while the ferrite laminæ have been colored by etching with Stead's reagent. This fact proves that the cementite was little affected by the action of the etching medium and consequently remained uncolored or relatively so. It is reasonable to expect that iron phosphide or solid solution of phosphorus in iron would behave in a similar manner and consequently remain uncolored after etching with Stead's reagent, as has been pointed out by Stead[15] to be the case.

(*d*) Whiteley[16] states that a cellular structure which he was able to develop in his low-carbon steel specimens was due to the phosphorus, this structure becoming more pronounced as the percentage of phosphorus is increased, and he offers the explanation of the formation of this cellular structure as being due to the absorption by gamma-iron of ferrite richer in phosphorus during the slow heating of the specimens up to temperatures above 815° C.

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[15] Stead, "Iron, carbon, and phosphorus," Jour. Iron and Steel Inst., 1915, **1**, p. 140.
[16] Loc. cit. (see footnote 12), p. 377.

VII. SUMMARY AND CONCLUSIONS

1. Two series of specimens, one of basic open-hearth steel and the other of acid open-hearth steel, with the phosphorus content in each series varied in four or five steps within the limits 0.008 to 0.115 per cent, which mark the ordinary limits of phosphorus content in plain carbon steel, were employed in the study of the relationship between the phosphorus content and the microstructure and hardness resulting from a series of different heat treatments tried.

2. Marked irregularity in the distribution and grain size of both the ferrite grains and pearlite kernels was found present in many of the specimens, particularly in the acid open-hearth steel series. However, no definite relationship could be established between this irregularity of structure and grain size and the phosphorus content and also the heat treatment.

3. No well-defined relationship could be established between the phosphorus content and the scleroscope hardness, though somewhat more satisfactory results were obtained for the Brinell hardness. Despite some irregularity in the results, there is a small but definite increase in Brinell hardness as the phosphorus content is raised.

4. The irregularity in the microstructure as mentioned in paragraph 2 was traced to the nonuniform distribution of the phosphorus in the steel.

5. In addition to the microstructure as developed for these steels, a cellularlike etch pattern was formed in conjunction with and apparently superposed upon the ferrite and pearlite structure. Relationship between this cellularlike structure and the distribution of the phosphorus content was established.

Acknowledgment is made to Dr. Henry M. Howe, at whose suggestion this investigation was undertaken, for suggestions concerning the outline of the experimental procedure followed in the work, the use of his laboratory apparatus, and also the set of phosphorus steel samples which had been furnished him by Dr. Unger as stated in the Introduction.

WASHINGTON, May 20, 1921.

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Bureau of Standards

DECEMBER 20, 1921

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CUTTING FLUIDS

By Eugene C. Bingham

ABSTRACT

Cutting fluids are used both to cool and lubricate. When lubrication is the more important, it is generally recognized that fatty oils are superior to mineral oils, although the reason has never been clearly explained. The evidence appears to be that the value of fatty oils is due to their residual valence or acidity which causes their adhesion to metal to be greater than is the case with mineral oils. If this should prove to be the case, it may yet be possible to synthesize an oil which has all of the virtues of lard oil without its obvious defects.

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PART 1. THEORY OF CUTTING FLUIDS

I. GENERAL

It is a curious fact that so many of the very common operations of our ordinary life are without adequate explanation. A case in point is the use of soap as a cleansing agent. It used to be said that the hydrolysis of the soap produced an alkali which saponified the grease, but this explanation is not in accord with the known fact that soaps act very well as detergents even when

the grease is one not capable of being saponified, for example, a paraffin oil; to state that the soap emulsifies the grease is strictly in accord with the facts, but it in no wise explains the phenomenon—it merely describes it.

So again, the use of lard oil or other liquid in various cutting operations in the machine shop is universally recognized as beneficial; but there is general disagreement as to the cause of the improvement which is brought about.

(*a*) COOLING.—In various operations, such as sawing, milling, planing, turning, boring, reaming, tapping, and parting off, the tool becomes more or less heated in use, and to prevent the overheating of the tool a stream of liquid over the work is naturally beneficial;[1] it is stated by many that the main purpose of a cutting fluid is as a refrigerant or "coolant." Following up this explanation we should expect that water with its very high specific heat and latent heat of vaporization would be the best cutting fluid.

Water is actually used for this purpose, but only to a limited extent. For drilling ship plates and boiler plates, water is said to give just as good results as cutting solutions or soluble oils. It is used for rough turning and for grinding. But it is generally objected to because pure water rusts the machines, and the work as well, if the latter is of iron or steel. Naturally this difficulty has nothing to do with the theory which we are discussing and it can be overcome by adding to the water substances like soda or soap which tend to prevent the formation of rust. Such solutions are used satisfactorily in drilling and grinding; they are also used on brass, copper, and aluminum, although a cutting fluid is generally regarded as unnecessary for these metals. The fact gradually emerges that with difficult work, water and simple aqueous solutions do not give a smooth finish and they slow down production because the tools become quickly dulled.

(*b*) LUBRICATION.—It has been observed that the greatest wear of a tool in cutting operations is often not at the point of the tool, but on its face at some distance back from the point. This is a striking and very significant fact. It is illustrated by a single figure (Fig. 1) taken from Taylor's Art of Cutting Metals. This is proof of the very great friction between the chip and the face of the tool at some distance back from the point. The chip often adheres to the tool so firmly that a "bead" of metal appears

[1] F. W. Taylor, Art of Cutting Metals, p. 15. The effect of cooling the tool through pouring a heavy stream of water on it permits an increase of 40 per cent in the cutting speed.

FIG. 1.—*Showing tool with "Cutting edge still good but deep groove worn or guttered in the lip surface by the pressure of the chip," from Taylor's Art of cutting metals, Fig. 17e. In other cases, small particles of the chips scraped from the forging are pressed or welded into a compact pile on the lip surface of the tool*

to be "welded" to the face of the tool so that it is necessary to remove it forcibly.

It has therefore been suggested that the cutting fluid acts primarily as a lubricant. Since the lubricant reduces the friction, the heat which otherwise would have been developed is avoided. If the lubricant also removes heat by conduction, so much the better. According to this theory water is unsatisfactory because its viscosity is so low that it has very little lubricating value, and "cutting fluids" and "cutting lubricants" become synonymous terms.

This theory has the obvious merit of explaining why no lubricant is necessary in cutting certain brittle materials such as cast iron. Cast iron has very great compressive strength, but since it is also very brittle a chip does not form; hence lubrication is unnecessary.[2] It also explains why it is impossible to get a smooth surface in machining certain metals without oils, even when the speed and depth of cut are reduced as far as practicable, whereas a perfect surface is obtained as soon as an oil is employed. Under such conditions it appears probable that the cooling action of the lubricant is unimportant, and thus in the extreme case it becomes a question of lubrication pure and simple.

But lubrication is another of those common operations for which there is no adequate theory up to the present time. Thus the theory gives little to guide one in the selection of an appropriate cutting oil. In taking a heavy cut at high speed, the theory would seem to call for an oil of high viscosity at room temperature, so that at the elevated temperature the oil would still have sufficient viscosity to carry the necessarily heavy load. If the cooling effect of the oil is taken into consideration, one must also take into account the specific heat of the oil. It is a fact, however, that these two properties are practically never given any serious attention in the selection of a cutting oil. Whether these properties should be so generally neglected remains to be discovered.

There are properties of oils which have no relation to the theory of cutting fluids, but which nevertheless have importance in practice. (1) Cutting fluids should not separate out solids at ordinary working temperatures; (2) their components should not become immiscible with each other in use; (3) they should be stable and neither oxidize in the air, give rise to gummy de-

[2] Graphite, present in cast iron, can of course act as a lubricant.

posits, nor carbonize as they pass over the work; (4) they should not be liable to spontaneous combustion as, for example, when exposed on cotton waste (combustible fluids should not be easily volatile because this adds seriously to the fire hazard); (5) they should not give off unpleasant odors when heated, even after continued use; (6) they should not injure the skin of the workmen either directly or by means of disease germs; (7) they should not corrode the work or the machines; (8) they should not injure the machine even if the cutting oil becomes mixed with the lubricating oil of the machine itself; (9) for some operations the cutting oils should be fairly transparent; (10) they must be readily obtainable.

Were these the only things to be considered, it would be easy to provide a cutting oil which would meet all of the requirements. One would select a petroleum oil of low cold-test and fairly high viscosity, having regard for the temperature of the oil in use. Most machine shops would effect a great apparent saving were they to use a straight mineral oil in place of the oils now employed for many classes of work. Before, however, we conclude that the practice of modern machine shops is unduly bound by tradition, it is well to inquire into the theory of lubrication, and particularly into the theory of cutting lubricants, to see whether there are any other possible factors which can affect the lubricating value of an oil.

(*c*) ADHESION.—It is well-nigh universal experience that pure mineral oils, regardless of their viscosity, have a very limited usefulness as cutting lubricants. Lard oil, on the other hand, is the cutting oil *par excellence*. Nevertheless sperm oil is practically the equivalent of lard oil, and this is the more remarkable because sperm oil is much more fluid than lard oil; it does not resemble lard oil in its chemical composition, since it is not an oil at all in the strictly chemical sense but a liquid wax. According to general testimony, olive oil and neatsfoot oil are nearly equal to lard oil; and aside from their tendency to oxidize in the air, rapeseed, cottonseed, corn, peanut, and linseed oils would serve very well. Aside from their objectional odor fish oils would be useful. There is therefore a fairly sharp differentiation between the so-called fixed or fatty oils and the mineral oils.

This experience of the machine shop demonstrates that viscosity is not the only measure of the "lubricating value" of an oil. But this conclusion is directly contradictory to the results of Tower's investigations on very well lubricated bearings, which showed

that the friction is dependent only upon the viscosity of the given oil. However, Tower's conclusions concerning ideal lubrication may be inapplicable to cutting oils, since these oils are used under conditions which are nearly the worst conceivable for effective lubrication.

The conclusion that viscosity is not the only measure of lubricating value is so highly important, not only in choosing a suitable cutting oil but in problems of lubrication in general, that it should not rest on hearsay evidence, no matter how widespread. We must inquire: What is the evidence upon which the machinist judges the fixed oils to be superior to others? Can this difference be measured quantitatively? Is there any similar preference for fixed oils in general lubricating practice or elsewhere? Is there any known property of fixed oils which can conceivably give them the supposed advantage?

In answer to the first of the above queries, it is very easy to demonstrate qualitative differences between the mineral and the fixed oils in a variety of ways. One finds differences in the smoothness of the finish of the work, in the speed of production, in the power consumption, in the life of the tool, and after a little experience one can judge the merits of the oils by the appearance of the shavings.

A skilled mechanic employed at this Bureau noted that in cutting off a rod of mild steel 1½ inches in diameter once, it was necessary to sharpen the tool 10 times when mineral oil was used; whereas with lard oil he could cut off the rod 8 times without resharpening. Moreover the cut surfaces of the latter were very smooth while the former were unspeakably rough.

This conclusion was confirmed by the author, by cutting off a series of disks from a bar of mild steel 1⅜ inches in diameter, using an Armstrong cutting-off tool on a direct-drive lathe, giving constant speed and feed. A mineral oil was used whose viscosity at room temperature was identical with that of a given sample of lard oil. The oil was dropped into the groove just ahead of the tool by means of a pipette in such a way as to obtain a fairly uniform flow. After some preliminary experiments which proved the striking superiority of lard oil, the author cut off 20 disks with lard oil in the effort to find out how many disks could be obtained with a single sharpening. This attempt was abandoned after examination of the edge of the tool with a compound microscope showed that the dulling was still not perceptible. The

surface of even the last disk was very smooth, as is shown in Fig. 2, *a*. After the tool was sharpened to remove any dulling that might have escaped detection and given as nearly as possible the same set as before, another disk shown in Fig. 2, *b* was cut off. All of the conditions were the same except that mineral oil was employed. The tool was badly dulled in cutting the first disk and broke in two on the fourth disk. The surface was very rough, as can be seen readily in the photograph. The chips were thrown out with violence and there was evidence of heating and heavy consumption of power. As to the nature of the individual chips, with lard oil the metal cut much like butter, the under side of the chip being perfectly smooth and the upper side finely corrugated. With mineral oil the corrugations were so deep that they extended completely through at the middle of the chip. This can easily be seen in the figure.

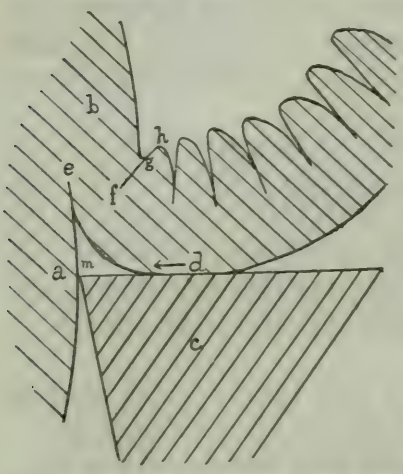

FIG. 3.—*Diagram to illustrate the relation of chip (d) to tool (c)*

To grasp the problems connected with this form of lubrication, it becomes necessary to consider in detail how the shaving is produced. Let *a* in Fig. 3 represent the body of metal from which the layer *b* is being removed by the tool *c*. The pressure of the tool at the point *d* wedges off the material and causes a fracture to extend into the work ahead of the tool at *e*. The point of the tool cleans up the rough surface, but the greater part of the pressure is exerted on the face of the tool at some distance back from the edge where, as has already been pointed out, the greatest wear occurs. The material in the region *f* is subjected to severe compression, and when the pressure reaches a certain critical value there takes place momentary plastic flow. The direction of flow *fg* is at an angle of approximately 45° with the pressure, which is taken to be normal to the surface *ad*.

As a result of the plastic flow the chip becomes about twice its normal thickness.[3] Since, however, the plastic flow can not begin

[3] The amount of thickening presumably depends on several factors, notably upon the friction of the chip on the tool as well as on the softness of the metal, cf. Taylor, Art of Cutting Metals, p. 119.

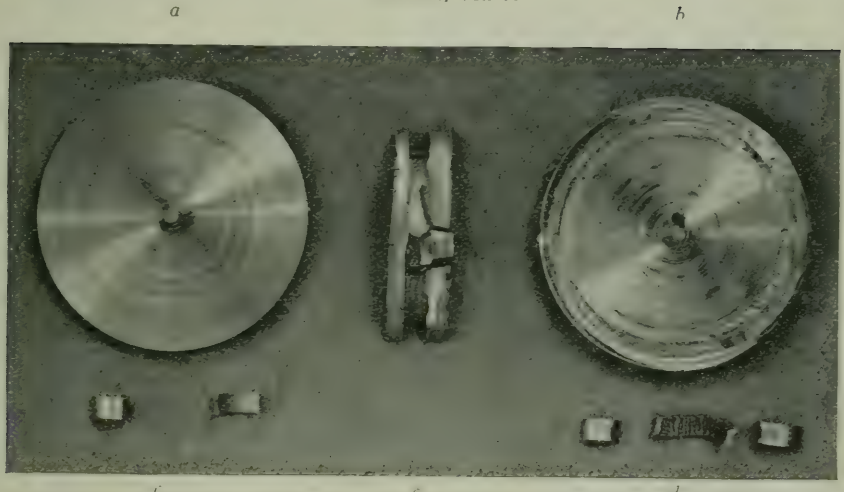

FIG. 2.—*Showing the difference in lubrication between lard oil (a) and mineral oil (b) in parting off mill steel rod*

The "bead" of metal which gouged into the surface of (*b*) may be actually seen at the middle of (*e*), where it formed on the tool. The chips with lard oil (*c*) are less deeply serrated than when using mineral oil (*d*)

until the pressure exceeds a certain value, known as the yield value,[4] there is a certain period during which the pressure is building up. During this time the shaving may move over the face of the tool and relieve the pressure somewhat, or the movement may be taken up by the slack in the machine or by the elasticity of the material. Supposing the parts to be strong enough, the pressure finally becomes so great that plastic flow results, and the material suddenly gives way, producing the characteristic projection of metal at *h*. During this period the pressure is falling off. We have therefore a cycle of rising and falling pressures, and corresponding with them we find corrugations on the upper surface of the shaving, which will be more or less pronounced according to the conditions.

The only useful work accomplished is that of wedging the shaving off. Nothing is gained from the plastic flow which takes place in the shaving, and yet in plastic flow relatively huge amounts of energy are required. So it may be taken as axiomatic that a lightly corrugated shaving is an advantage, since it is an indication of good lubrication and small amounts of plastic flow. That it is highly important to get a lubricant between the tool and the shaving at the point *d* is probably self-evident. That plastic flow occurs in the formation of the chip and that the energy used up in producing it is valueless accord perfectly with the views expressed by Taylor in explaining the baffling fact that there is no traceable relation between the pressure of the chip on the tool and the possible cutting speed. The pressure of a soft steel upon the tool is great because a larger amount of energy is consumed in plastic flow of the material of the chip than is the case with a hard steel.

Assuming that the metal at *f* is wedged away from the body of material as already indicated, there will be formed a space *m*, the size of which is continually varying but is dependent upon the conditions of work. Into this space the lubricant may be drawn, since the pressure upon a fluid in this space would be both small and variable in amount. From this space the lubricant would be drawn along by the chip to the point *d* where the pressure is excessive.

Owing to the friction between the shaving and the face of the tool, a force is exerted upon the shaving (indicated in the figure

[4] B. S. Bull. 13, p. 309, 1916; Proc. A. S. T. M., 1919; Pt. II, pp. 641–664, 1919.

by the arrow) which is parallel to the surface and in the direction *da*. If the frictional force is small, the pressure on the face of the tool will be continually relieved and plastic flow will take place only near the outside surface of the chip, in which case the corrugations will be shallow, cf. Fig. 2, *c*. If, on the other hand, the frictional force is great, a correspondingly greater amount of relief from the pressure will have to be obtained by means of plastic flow. The corrugations will be deep and the shaving therefore fragile, cf. Fig. 2, *d*. The wedging action will be interfered with and the space *m* will be reduced in size. Plastic flow will take place not only outward, but also inward toward the point of the tool. Thus the metal in the whole region of *f* will be gathered into a bead of metal, which will gouge into the metal at *a* or force itself either laterally (at right angles to the plane of the paper) into the metal at the sides of the cut, as shown by the disk in Fig. 2, *b*, or down over the edge of the tool, thus destroying it.

This phenomenon is particularly well shown by Fig. 2, *e*. At the right is the disk which was being cut off, at the left is a portion of the rod, and in the center is the groove made by the tool up to the time that it broke. A part of the metal has been cut away in order to let in light to aid in taking the photograph. Two beads which flow together at the middle can be seen plainly just ahead of where the tool was. This demonstrates plastic flow. This bead of metal gouged deeply into the bottom and either side of the cut. In the photograph one can easily detect the burr thrown up at the left by this process of gouging.

Having formed a conception of the method by which the shaving is produced and having arrived at a conclusion as to the exact function of the lubricant, we can better proceed in our inquiry as to the cause of the marked superiority of the fixed oils.

In examining the properties of the oils which might account for a difference in behavior, we find that lard oil has a lower temperature coefficient of viscosity than any of the common mineral oils. Lard oil therefore possesses an advantage over a mineral oil in that, although it is relatively fluid at ordinary temperature, it does not lose its viscosity rapidly at high temperatures. This explanation is good as far as it goes, but unfortunately it is not adequate. In the results obtained sperm oil is practically equal to lard oil, although it has a very much lower viscosity at ordinary temperature. Castor oil is the opposite extreme in having a very high viscosity at ordinary temperature and it is like the mineral

oils in having a high temperature coefficient of viscosity, yet "for finish boring, rifling, etc., a mixture of castor oil and mineral cleaning oil has been used with good results." [5]

Moreover it is hard to believe that in light surfacing operations at low speed where mineral oil often fails, the temperature is high enough to seriously affect the viscosity. The true explanation appears to be more fundamental.

It is sometimes stated that the temperature of the oil film in a bearing is widely different from the temperature of the bearing or of the body of the oil. We should therefore compare the viscosities of oils at the temperature of the oil film. To determine the temperature of the oil film a shallow cavity was made in the center of the bearing on the friction testing machine, and in this a thermocouple was placed so as to be surrounded by oil, at a point where the shear would be greatest. At the same time the temperature of the bearing was taken by means of a thermometer. It was found that the difference between the two readings was hardly preceptible, amounting to less than a degree. Hence, we assume that under suitable conditions the temperature of a bearing may be safely taken as the temperature of the oil under shear. This does not apply to conditions of incipient seizure, but there the conditions are hardly steady enough to give definite values.

The effect of pressure upon the viscosities of oils must also be considered. Assuming the correctness of the law [6] that the fluidity of a liquid of given chemical composition varies in direct proportion to its free volume, we should expect the mineral oils to be superior to the fixed oils in difficult cases of lubrication, for the reason that the mineral oils appear to be more compressible than the fatty oils. This is borne out by experiments which are referred to elsewhere.[7] It is also in harmony with the fact which we have repeatedly observed that the superiority of lard over mineral oils is very pronounced in light surfacing operations on "draggy" metals, and that the character of the mineral oil can be greatly changed by very small additions of a fatty acid.

There is a property which is entirely adequate to account for the differences noted, although it has not been sufficiently recognized in the past. It is the property of *adhesion*. That oil which adheres to the metal most strongly will most quickly form a film and most stubbornly resist all efforts to rupture it.

[5] Bulletin No. 2, Advisory Council of the Department of Scientific and Industrial Research (London); 1918.

[6] J. Amer. Chem. Soc., **36**, p. 1,393; 1914.

[7] Engineering, **108**, p. 755; 1919.

When a plane, horizontal steel disk is carefully lifted off from a surface of clean mercury, the force required per unit area is a measure of the adhesion of the mercury for the metal. If the adhesion of the liquid for the plate, however, is greater than the cohesion of the liquid—that is, if the liquid wets the plate—lifting the plate will disrupt the liquid, and we get not a measure of the adhesion of the liquid for the plate but of the cohesion of the liquid. Since most solids are wet by most liquids, we have a large amount of data on surface tension or cohesion, but only in exceptional instances like the above have we any idea of how strongly a given liquid wets or tends to wet a particular solid. There can be no doubt but that specific adhesion is as characteristic a property of matter as specific cohesion. Cohesion appears to be of comparatively little interest in lubrication, whereas adhesion is of prime importance.

Although physicists are not accustomed to measure adhesion, there can be no doubt but that the need for data on this or some similar property is recognized in the literature. Thus in papers on lubrication there are continual references to the "oiliness" of the lubricant, its property of "greasiness," "unctuosity," "slipperiness," and also its "lubricating value" or "body" when these terms are used as distinct from viscosity.

Of course there terms are loose, and they have never been sufficiently well defined. However, the ideas of Archbutt and Deeley on this subject are clear. "Mineral oils,[8] unlike animal and vegetable oils, seem for the most part deficient in this property of forming thick, permanent films. Experiment [9] has shown that whereas at low speeds greasiness is an all-important factor, in perfect lubrication at high speeds, viscosity plays the more important part. At very low speeds[10] * * * the lowest coefficient is obtained by the use of fatty oils."

The flotation process of separating minerals is not well understood, but it is apparently based upon adhesion. Thus, for example, Megraw[11] states "froth flotation depends in part upon adhesion." He goes on to say that "although it may be proved that this statement is technically accurate, it is very difficult to go back of it and explain what adhesion is." Advantage is apparently taken of the fact that for every liquid and every solid there is a particular specific adhesion. Hence, if a pulverized ore con-

[8] Lubrication and Lubricants, p. 56; 1912.
[9] Lubrication and Lubricants, p. 371.
[10] Lubrication and Lubricants, p. 442.
[11] Flotation, p. 32.

taining two or more minerals is thrown into water containing a little oil, those particles for which the oil has the greatest adhesion will eventually get the oil. Hence, it is theoretically possible to separate any two minerals. Practically, the metallic sulphides are found to be most readily wet with oil while the metallic oxides and silica appear to be much less readily wet. Of the variety of oils that have been used, oil of pine, lard oil, cottonseed oil, fish oil, and mineral oil should be mentioned. It is an anomalous fact that "of the Texas crude oils[12] there seems to be none so far tested that can be depended upon to give satisfactory results alone. * * *. In combination with either pine, oleic, or pine-tar oils they give good results." It is astonishing to discover for the first time how many valuable materials are concentrated by taking advantage of differences in adhesion. The process of obtaining zircon and the diamond by means of the "grease board" is certainly striking.

Not only in ordinary lubrication and in the flotation process of ore separation have we evidence that the property of adhesion is useful, but there is a considerable mass of confirmatory evidence in the literature. While this paper was being prepared for publication there appeared a valuable paper on "Cutting lubricants" by the Advisory Council of the Department of Scientific and Industrial Research (London), Bulletin No. 2,[13] in which it is frankly stated "Where a perfect finish is desired, experience has shown that cutting oils possessing great oiliness must be applied."

We may, therefore, take it for granted that there exist a number of different phenomena, quite clear cut in character, which are not explained by any property which has been clearly understood and measured up to the present time.[14] These phenomena can apparently be explained on the basis of variable coefficients of adhesion. To test this hypothesis it remains (1) to inquire whether the adhesion is of sufficient magnitude to account for the observed effects, (2) to suggest possible methods of measurement, and (3) to discover how nearly the results of measurements agree among themselves as well as with the practical results of adhesion which seem to have been observed.

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[12] Flotation, p. 54.

[13] See p. 3.

[14] Since this was written a number of valuable papers have appeared dealing with this subject, cp. "Report of the lubricants and lubrication committee of the Advisory Council of Scientific and Industrial Research, London (1920); Wells and Southcombe, Jour. Soc. Chem. Ind., p. 517 (1920); Hardy, "Proc. of the Roy. Soc. of Great Britain," Feb. (1920); etc.

We are quite accustomed to think of surface tension as being an effective force in capillary spaces. Since wherever a liquid wets a solid the adhesion must exceed the cohesion, we can state definitely the minimum order of magnitude of the force in which we are here interested. How much greater the adhesion may be than the cohesion we are unable to state, but there is apparently no reason why it should not greatly exceed it in some cases. If we may estimate the adhesion by the heat which is liberated when a solid absorbs a liquid or a gas, the adhesion in certain instances is enormously great. This is particularly true if we regard chemical union simply as a form of adhesion. There is reason for believing that these forms of adhesion grade insensibly into each other. Stating it in another way, there is probably a connection between adhesion and chemical composition.

But adhesion is extremly susceptible to the action of impurities. Thus the adhesion between steel and mercury is stated to be less than the cohesion of mercury. If, however, a file is broken under mercury, or if the file is dipped in sodium amalgam, it becomes wet with mercury. This shows that adhesion is normally reduced by impurity consisting probably of a layer of oxide.

Oils will not wet many solids in the presence of a dilute alkali. On the other hand, the adhesion of oils is greatly increased by the presence of an acid in solution. In the flotation process sulphuric acid is commonly added, but a deflocculating agent never; that is, the adhesion of the oil for the mineral is kept as high as practicable.

We know something of the adhesion between solids and this knowledge is of value to us in connection with our study of cutting oils. When two solids are brought into contact they always adhere. Whether the adhesion becomes perceptible or not depends upon the number of points which are in direct contact. Owing to the difficulty of getting more than three points of one surface into contact with another, the force of adhesion is usually not very great. Generally speaking, if a piece of metal or porcelain is broken in two, the pieces can not be made to adhere strongly by any treatment short of fusion, but a study of the matter shows that the difficulty is simply that of keeping the surfaces clean and getting them into general contact. Thus, if a fine metallic powder is subjected to pressure, it will become a solid mass of metal without the temperature being raised to the fusing

point. It is common knowledge that pieces of plate glass, when brought together, adhere strongly and can be separated only with difficulty. That this phenomenon is due to adhesion and not to atmospheric pressure can be proved by attempting to separate plates in a vacuum.

The Johannsen and Hoke blocks, used in gage testing, have very carefully made "true" surfaces. Since the more nearly perfectly two surfaces are cleaned, polished, and fitted together the better they will adhere, we might expect these blocks to cling together. As a matter of fact, a pile of these blocks many centimeters high can be lifted by raising the top one. A still more striking instance of adhesion is found in the commonly recognized experience that in "lapping out" a bearing a point can be easily reached where, if no lubricant is used, and with only the pressure of the fingers, the journal and bearing will "seize" with a very slight turn of the one inside the other. Yet no force will separate them again and a photomicrograph of the section across the surface of union will give the appearance of a perfect weld.

It is a significant fact, which is overlooked, that no pure liquid is immiscible with itself. If the strong cohesive forces which hold the liquid together were withdrawn, it would suddenly become a gas. The mere fact of the existence of liquids and solids is proof of their strong cohesion. This is an important fact. Miscibility of liquids or solids occurs when the adhesion between them becomes great enough to overcome their individual cohesion.

It is a noticeable fact that, as a general rule, substances are often most soluble in those substances to which they are most akin, thus paraffin hydrocarbons are mutually miscible, etc. Sulphur is soluble in several compounds of sulphur, for example, carbon disulphide, ammonium sulphide, sulphur chloride. Without pressing this further it is certain that iron must adhere strongly to iron whenever two perfectly clean surfaces are brought in close contact. On the other hand, foreign substances brought between these surfaces may be expected to decrease this adhesion. Faraday[15] noted the peculiar friction there is when a platinum rod is rubbed over a thoroughly cleaned platinum plate. Lord Rayleigh[16] called attention to the extraordinary sliding friction between two thoroughly clean glass surfaces.

Langmuir[17] stated that "if glass was forced to slide over glass a squeaky noise was always heard if the glass was clean, and the

[15] Exper. Researches, p. 369. [16] Phil. Mag., 35 (6), p. 157; 1918. [17] Private communication.

surface of the glass was scratched perceptibly in the process." In other words there was *seizure*. Extending the work of Miss Pockels and Lord Rayleigh, Langmuir has devised a "talc test" by means of which the contamination of a surface may be determined, and he has studied the sliding friction with various kinds of contamination. Using a glass slider on a glass surface it was found that the latter could be tilted usually to an angle of 70° from the horizontal, often to 75° and in some cases 90° or even 92°, before the slider would begin to move.

The "sliding angle" of glass on glass was found to be 60°; that of glass on mica and of platinum on mica was 10°. Similarly the sliding angle of platinum on platinum was 35°, whereas for glass on platinum it was 30°. In each case the sliding angle was lower when the materials were different. Of course, the results are too few to admit of generalization. In every case the sliding angle was greatly lowered by adding a monomolecular layer of oleic acid.

In lubrication it is of paramount importance to keep the surfaces from coming into contact, for wherever the solid surfaces touch adhesion will occur. The problem of lubrication is theoretically one of great simplicity. The two metals are prevented from seizure by means of a third substance which may be a solid such as graphite or talc, a liquid such as lard oil, or even a gas such as air. If the third substance is a solid, it must be soft so that it will readily undergo plastic flow. If it is a liquid, it must adhere strongly and it must not be too fluid, lest it squeeze out.

The cutting of metals offers the most severe conditions for lubrication. The tool is continually taking off fresh metal, often at a high rate of speed and at high temperature. The pressure of the chip upon the tool is sometimes excessive. All of these causes tend to make adhesion between the chip and the tool very great and the need for a lubricant to prevent seizure may be imperative. That lubricant is best which has the greatest adhesion for the metal, since it is most strongly drawn into the space between the tool and the metal being removed.

Caution needs to be taken not to draw too broad inferences from the above statement. Thus in cutting brittle substances, such as glass or very hard steel, a shaving is not formed and lubrication is unimportant. In fact, seizure is apparently desired in order to get the tool to "bite." What is needed therefore is something which will clean the surface and cool the tool. Turpentine, either

FIG. 4.—*Showing a piece of cast iron whose surface was smeared with lard oil (a), castor oil (b), oleic acid (c), and turpentine*

Where the oil was the work appears lighter colored, owing presumably to smoother finish. In the case of turpentine there was no observable effect

alone or with camphor, is often used for this class of work. The function of the camphor remains unexplained. Water may also be used. It is a general custom among workmen to moisten a file with saliva before using it to cut glass. The liquid in these cases plays somewhat the part of the soft nose on the armor-piercing projectile, which increases the friction between the armor and the shell, thus causing the shell to "bite."

The cast-iron cylinders of marine engines are not lubricated. It has been suggested that the graphite of the iron acts as a lubricant. We have, however, no positive foundation for this statement. A lubricant is not ordinarily employed in machining cast iron, but it can readily be shown that a lubricant other than the graphite of the iron has a pronounced effect. For example, in planing off a thin layer of metal from a block of cast iron an oily finger mark on the original surface will be reproduced on the final one as shown by the photograph reproduced in Fig. 4. Where the metal was barely moistened with lard oil, castor oil, or oleic acid, it received a smoother surface which makes it appear lighter colored in the photograph.[18] Where the oil was the tool did not "bite" in as deeply as elsewhere. By actual measurement these spots were about 0.01 mm higher than the surrounding metal. Turpentine was without effect or possibly caused the tool to "bite" a little deeper than before. To prove that the spots are not due to the presence of oil on the surface when photographed, the whole block was immersed in oil and allowed to stand for several months before the photograph was taken.

It has been suggested that the fixed oils have greater adhesion for metals because the free fatty acid[19] has a chemical affinity for the metal, with which it tends to form a metallic soap, which in turn attracts the oil. Experiments can easily be devised to test this interesting suggestion by adding small amounts of fatty acids to mineral and other oils. It is certain that a glass or metal surface wet with an oil in the presence of alkali can readily be washed clean, which is not the case when the oil is contaminated by a fatty acid.

(*d*) Measurement of Adhesion.—1. If a solid is moistened by a liquid, heat must be developed. It has been shown that in certain instances this heat is considerable and that it varies according to

[18] The apparent fastidiousness of the mechanician, who sometimes objects to having his half-finished work handled lest it show finger marks is readily explicable.

[19] Wells and Southcombe, see footnote 14.

the liquid used. Thus the heat of wetting of a sample of amorphous silica with water was found to be 18.54 cal. per gram.[20] If we can assume the surface area per gram of material to be constant, we may fairly take the heat developed with different liquids as a measure of their relative adhesion.

2. The rate of wetting of a surface offers a possible measure of adhesion. For example, two disks of glass were ground to an optically flat surface, carefully cleaned, and placed so that their surfaces were touching at one edge, but kept apart a definite distance at the opposite edge. The space between being wedge shaped, a drop of oil placed at the wide part of the wedge was immediately drawn by adhesion up into the point of the wedge. Taking the time required for the oil to pass over a certain specified distance, a measure of the relative adhesion was obtained. Using a lard oil and a mineral oil having the same viscosity, the former took an average time of 133 seconds and the latter an average of 87.6 seconds. Unfortunately it appears to be very difficult to clean a metallic plate so that an oil will wet it evenly and give consistent results by this method.

3. If a small flame is placed underneath a corner of a square plate of steel or brass and a drop of mineral oil is placed on the heated spot, the oil will rapidly move toward the cooler portions of the plate, the edge of the drop of oil forming ever-widening arcs of circles and the oil becoming an ever-thinner layer. If lard oil is used it moves much more slowly and the appearance of the drop is also very different. The oil does not thin out evenly, but it finally collects in a great number of droplets following a characteristic pattern. In one experiment with the temperature of the hot spot 200° C and the opposite corner of the plate at 30° C lard oil required 292 seconds to move a distance of 7 cm, while a sample of mineral oil having the same viscosity at 25° C moved the same distance in only 70 seconds. Manifestly it is desired of a lubricant that it move away from a hot spot as slowly as possible.

4. Since the force of adhesion can affect only those molecules which are distant from the metal only a few molecular diameters at most, the vapor pressure of an oil may have an important influence in the case of an oil which tends to leave a heated surface. An oil with a high vapor pressure would distil from a point of high temperature to another point of lower temperature. This tendency on the part of an oil is certainly a disadvantage, but we

[20] Bellatti and Finazzi, Att. Inst. Veneto, **59**, II, p. 931, 1900: and **61**, II, p. 503, 1902.

can not claim a direct proportionality between vapor pressure and adhesion. The fixed oils are characterized by a very small vapor pressure as compared with even the heavy mineral oils. Thus lard oil has a probable boiling point of 580° C, while a mineral engine oil was found to have a boiling point around 330° C. There must be a lowering of the vapor pressure of the absorbed film which is a function of the adhesion.

5. In grinding a given pigment in oil it has been noticed that the amounts of different oils required to give a paste of a given consistency vary very widely, and in a manner which can not be accounted for by the viscosity. It is quite possible that the effects are due to the different adhesion of the pigment for the various oils. It is suggested therefore that a given powder be ground in a similar volume percentage of oil and that the yield value [21] be measured.

6. In addition to the above there are practical methods. It appears that the so-called friction testing machine can sometimes be used to measure adhesion. It would appear probable that with a given bearing and two oils of the same viscosity, the oil having the lower adhesion would squeeze out first. It has often been stated that glycerol and molasses are absolutely devoid of lubricating value, although they have the requisite viscosity. If this is the case, then it ought to be readily possible to make a set of similar bearings and, having "run them in" on a friction-testing machine, to test different lubricants for the maximum load which each would carry before seizure took place. The author has devoted a large amount of labor in following up this lead. The only important result of his study is to prove that, with well-fitting bearings bathed in lubricant, glycerol, sugar solution, and gelatin solution will undoubtedly function as lubricants. We continued to dilute these materials with water until we obtained a viscosity of only 45 seconds, Saybolt, without obtaining seizure at a load of 800 lbs./in.^{2}. The machine used was of the "Cornell" type, with a journal 3¾ inches in diameter and 3½ inches long. The bearing block of lead-calcium alloy was 2 inches wide, thus providing a projected area of test bearing of about 7 square inches.

7. The flotation methods seem to offer at least a qualitative measure of adhesion.

8. It is possible to get comparative results from experiments in cutting a given metal under constant conditions of speed, feed,

[21] Cf. B. S. Bull., 13, p. 309; 1916.

rate of application of cutting liquid, etc. Power consumption, torque, finish on the work, and speed of production, and dulling of the tool all offer possibilities of measurement. Taylor[22] has worked out a "standard cutting speed" which should be given careful consideration by any one proposing to measure adhesion by this method. He used the cutting speed in feet per minute which would cause the tool to be completely ruined in 20 minutes under standard conditions.

9. A number of variations of the above methods will readily suggest themselves. It has been shown that when solutions of various electrolytes are filtered through clay, a portion of the electrolyte is adsorbed. So, if a metal powder were shaken up in a solution of oil in some solvent like ether and then centrifuged, it might be found that the amount of oil retained was a function of the adhesion between the metal and the oil. The author has shown elsewhere[23] that if a mixture of two liquids is forced through long, fine, capillary tubes or pores, such as are found in a column of clay, the rate of flow will be affected by the relative adhesion of the two liquids for the solid material. There will, therefore, result a partial separation of the components of the mixture. Such a separation has been demonstrated by Gilpin and his coworkers in connection with petroleum. This method might be applied to lubrication by forcing the two oils to be compared through powdered metal until an equilibrium is established, when the adhering oil could be extracted and analyzed.

10. In connection with the measurement of adhesion we may refer to the change of surface energy when 1 cm^2 of interface is formed between two liquids, as measured by Harkins. He has obtained the following values, which are of great interest:[24]

	Ergs
Water *vs.* water	145.6
Ricinoleic acid *vs.* water	94.9
Caprylic acid *vs.* water	93.7
Octyl alcohol *vs.* water	91.8
Oleic acid *vs.* water	89.0
Castor oil *vs.* water	87.7
Ethyl ether *vs.* water	79.2
Benzene *vs.* water	66.2
Paraffin oil *vs.* water	47.8
Hexane *vs.* water	41.2

The adhesion of liquids to water seems remote from their adhesion to steel and other metals. But according to the views of

[22] Art of Cutting Metals, p. 41.
[23] B. S. Bull., 13, p. 324; 1916.
[24] J. Amer. Chem. Soc., 39, pp. 354, 541; 1917. See also Southcombe, Engineering, 109, p. 184; 1920.

Langmuir and also of Harkins, adhesion is dependent upon the presence of active groups in the molecules, the hydroxyl group, carboxyl group, double bond, etc. When a layer of oil only 1 molecule deep is placed on water or a solid surface there is a distinct change of properties, as shown by Miss Pockels and Lord Rayleigh. Results privately communicated by Dr. Langmuir show that a layer of paraffin oil can be readily washed off from a surface of glass, mica, calcite, platinum, sphalerite, galena, pyrites, or magnetite by simply passing the contaminated surfaces through a gentle stream of running water. But in every case it was found to be impossible to remove the greasiness due to oleic acid by repeatedly passing through a stream of water. He says:

> We may assume that the attractive force between hydrocarbon molecules and the solid surface is greater than that between hydrocarbon molecules, but active groups like those contained in water or oleic acid are attracted to the solid surface very much more than are hydrocarbon molecules. The paraffin oil thus readily wets the solid, if brought into contact with it, but the hydrocarbon molecules are readily displaced from a surface layer when water or oleic acid is present.

This is exactly in accord with our own ideas arrived at from a different point of view.

11. Langmuir has noted that fairly constant results were obtained in the use of the slider referred to above by starting it in motion down the inclined plane of glass and noting the angle at which motion just stops. For example, if oleic acid or other oily substance is put on and then thoroughly wiped off, the sliding angle is reduced from 50 down to 6 to 10°. Paraffin oil lowers the sliding angle nearly as effectively as oleic acid, presumably owing to the fact that the active group of oleic acid is in contact with the glass, so that the free ends of the molecules are the same in both cases. Whatever the explanation, this is evidently not a possible method for the measurement of adhesion.

Langmuir has also measured the contact angle of a drop of water with various surfaces contaminated with oleic acid.

Thus he gets:

	Degrees
Mica	24
Quartz	31
Glass	42
Platinum	72
Calcite	82
Sphalerite	92
Galena	106

These results are specific, but it is too soon to say exactly what is their significance.

II. CONCLUSION

Cutting oils are used partly on account of their cooling value, partly on account of their value as lubricants. But the value of an oil as a cutting lubricant is not measured by any known test. Apparently a high adhesion of the oil for the metal is necessary. A number of methods are suggested for the measurement of this quantity, but its maximum development seems to be dependent upon residual chemical activity, such as is present in oleic acid. According to this view the prevalent practice of excluding as far as possible free oleic acid from a cutting oil is shortsighted. We can even go further and predict that for many, if not all purposes, it may yet be possible to synthesize an oil which has all of the virtues of lard oil without its obvious defects. Thus sulphur in the free condition or as sulphide possesses a great amount of residual affinity. Many oils when heated with sulphur dissolve it to a greater or less extent. Pine oil, which is largely used in flotation, has residual affinity which causes it to absorb sulphur readily. The product we have found to possess great virtue as a cutting oil either by itself or diluted with large amounts of mineral oil. For it is to be noticed that, if our argument is correct, small quantities of a substance of high adhesive qualities will entirely alter the properties of an inferior oil. Others have noted the fact that the properties of an oil are greatly altered by small amounts of impurities. Miss Pockels showed that the behavior of purified oil is quite different from that of the common oil. Richter states that the tendency of oil to spread on water is due only to the free oleic acid contained in it. Lord Rayleigh showed that when sufficiently purified "the drop remains upon the water as a lens, and flattens itself out, if at all, only very slowly."

To test this further the author made a series of experiments. In correspondence and conference with a large number of practical users of cutting oils in quantity, it was found that some users were convinced that regardless of cost, or convenience, certain oils sold under trade names were indeed superior to even the best lard oil. Some of the best oils according to general consensus of opinion contain sulphur in large quantity. On analysis one showed 5.5 per cent sulphur, and not only blackened copper but evolved large quantities of hydrogen sulphide when boiled. Apparently it contained a considerable amount of pine

oil. There was an odor of phenol which was probably used in very small quantity merely for the sake of its odor. Even without phenol it would probably be germicidal, and testimony is that in working with such an oil the men have been unusually free of the customary infections. With a knowledge of the proper composition of cutting oils, users should be able to write specifications more intelligently, thereby securing better oils, and with the possibility of supplying their own needs they may be able to secure better terms.

PART 2. TESTS

I. DETERMINATION OF SPECIFIC HEAT, DENSITY, SURFACE TENSION, VISCOSITY, AND LUBRICATING VALUE OF TYPICAL OILS

(By A. W. C. Menzies, W. G. Kleinspehn, G. Q. Lewis, and Eugene C. Bingham)

In the study of cutting oils in particular and the question of lubrication in general, it seems necessary to determine the different properties of fixed and mineral oils which may possibly produce the effects upon their value as lubricants, which we have been discussing. A. W. C. Menzies has determined the specific heat, surface tensions, and densities of certain oils. He used cottonseed oil, castor oil, and a commercial brand of naphthene-base oil "U." The samples were furnished by this Bureau. In the case of the first two, the oils themselves were used as calorimeter fluid, and the rise in temperature was observed when a perforated brass cylinder of known heat capacity and at known temperature was dropped into the calorimeter. In the case of castor oil, the viscosity was so great that the above method was not satisfactory. The oil was therefore placed in a 25 cc cylindrical glass bulb furnished with a calibrated capillary so as to form a very sensitive thermometer, whose readings were compared with those of the calorimetric thermometers. The castor-oil thermometer, taken from a chamber at 0° C was immersed in a water calorimeter and readings made at simultaneous temperatures of calorimeter and castor-oil thermometer. Due correction was made for the heat capacity of the glass of the bulb. The calorimetric thermometers were supplied with Reichsanstalt certificates of corrections rounded to fiftieths.

TABLE 1.—Specific Heats of Oils

Kind of oil	Temperature rise in degrees centigrade	Specific heat
Cottonseed oil	(1) 20.6–28.6	0.4537
	(2) 21.3–29.3	.4502
Average specific heat at 25.0° C		.452
"U" oil	(1) 19.1–27.9	.4141
	(2) 21.4–29.9	.4122
Average specific heat at 24.6° C		.413
Castor oil	(1) 0.0–20.5	.487
	(2) .0–20.5	.478
Average specific heat at 10.2° C		.483

Each of the specimens of oil was previously freed from water and dissolved gases by heating at 180° or higher in a vacuum. The densities were determined in a quartz glass dilatometer. Temperatures were measured with a set of Allihn type thermometers, of satisfactorily constant zero points, furnished with Reichsanstalt certificates to 0.1° up to 200° and to 0.2° above 200°. The threads were completely immersed. Surface tensions were measured in a glass capillary tube of radius 0.3254 mm, and the data assume a zero angle of contact with the glass. The lower meniscus had a diameter of over 34.2 mm. Due regard was given to the remarks of Richards[25] in reference to the measurement of surface tension. Violently stirred baths of a lard substitute and of fused nitrates were used to maintain uniform temperatures.

TABLE 2.—Density and Surface Tension of the Furnished Specimen of Cottonseed Oil

Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²	Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²
20	0.920	32.7	130	0.847	24.4
30	.913	31.0	140	.840	23.7
40	.907	31.1	150	.834	23.1
50	.900	30.2	160	.827	22.5
60	.893	29.4	170	.821	21.9
70	.886	28.6	180	.814	21.3
80	.880	27.9	190	.808	20.7
90	.873	27.1	200	.801	20.1
100	.867	26.4	210	.795	19.5
110	.860	25.7	220	.788	18.9
120	.854	25.0	230	.782	18.4

NOTE.—The oil was freed from dissolved gases and water by heating at 200° C in a vacuum.

[25] J. Am. Ch. Soc., 37, p. 1674; 1915.

TABLE 3.—Density and Surface Tension of the Furnished Specimen of Naphthene-Base Oil, "U"

Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²	Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²
0	0.942	32.5	140	0.849	21.1
10	.940	31.5	150	.842	20.5
20	.929	30.6	160	.835	19.8
30	.922	29.6	170	.829	19.2
40	.915	28.7	180	.823	18.6
50	.908	27.8	190	.817	18.0
60	.901	27.0	200	.811	17.4
70	.895	26.2	210	.805	16.8
80	.888	25.4	220	.799	.....
90	.881	24.6	230	.792	.....
100	.874	23.9	240	.786	.....
110	.868	23.2	250	.780	.....
120	.861	22.5	260	.774	.....
130	.855	21.8			

NOTE.—The oil was freed from dissolved gases and water by heating at 180° C in a vacuum.

TABLE 4.—Density and Surface Tension of the Furnished Specimen of Castor Oil

Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²	Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²
20	0.957	34.0	130	0.879	24.9
30	.950	33.0	140	.872	24.2
40	.943	32.1	150	.865	23.5
50	.936	31.2	160	.858	22.9
60	.929	30.3	170	.851	22.3
70	.922	29.5	180	.844	21.7
80	.915	28.7	190	.837	21.1
90	.908	27.9	200	.829	20.5
100	.901	27.1	210	.822	19.9
110	.894	26.3	220	.815	19.3
120	.886	25.6	230	.808	18.8

NOTE.—The oil was freed from dissolved gases and water by heating at 200° C in a vacuum.

The surface tension curves for these three oils are nearly identical.

W. G. Kleinspehn has measured the fluidities of cottonseed oil, linseed oil, and other oils. The method is that already described by Bingham.[26] The measurements were in duplicate. The data are given in Table 5.

[26] B. S. Bull., 14, p. 59; 1917.

TABLE 5.—Fluidities of Several Oils

COTTONSEED OIL

Temperature in degrees centigrade	Limb of viscometer	Time in seconds	Specific volume	Density	P_o	P	Viscosity	Fluidity
			cm^3/g	g/cm^3	g/cm^2	g/cm^2		
0.7	L	807.0	1.073	0.8070	289.77	289.77	184.29	0.5425
	R	807.8	.....	.....	289.59	289.59	184.36	.....
10	L	482.2	1.080	.9260	289.73	289.72	110.11	.9079
	R	482.7	.....	.....	289.57	289.56	110.16	.....
20	L	615.9	1.088	.9190	139.39	139.39	67.66	1.478
	R	616.4	.....	.....	139.26	139.39	67.65	.....
30	L	316.1	1.096	.9123	178.07	178.05	44.36	2.255
	R	316.3	.....	.....	177.86	177.84	44.34	.....
40	L	352.0	1.104	.9055	110.69	110.68	30.70	3.257
	R	352.5	.....	.....	110.55	110.54	30.71	.....
50	L	386.6	1.113	.8988	72.82	72.81	22.18	4.508
	R	388.0	.....	.....	72.60	72.59	22.20	.....
60	L	596.2	1.121	.8924	35.74	35.74	16.79	5.957
	R	597.0	.....	.....	35.68	35.68	16.79	.....
70	L	469.4	1.129	.8860	35.10	35.09	12.98	7.709
	R	464.0	.....	.....	35.45	35.44	12.96	.....
80	L	363.8	1.123	.8904	30.83	30.80	8.84	11.32
	R	366.3	.....	.....	30.68	30.62	8.85	.....
90	L	300.9	1.132	.8835	30.71	30.67	7.28	13.70
	R	303.0	.....	.....	30.62	30.60	7.32	.....
100	L	253.2	1.141	.8765	30.82	30.78	6.15	16.26
	R	255.0	.....	.....	30.71	30.67	6.17	.....
				"U" OIL				
10	L	6054.4	1.069	0.9353	411.70	411.30	1,964.50	0.051
	R	6067.3	.....	.....	411.30	410.25	1,965.70	.....
20	L	2086.6	1.077	.9286	410.56	409.02	675.15	.148
	R	2086.8	.....	.....	410.26	409.85	674.75	.....
30	L	856.4	1.084	.9225	409.85	409.43	276.62	.362
	R	856.2	.....	.....	409.73	409.34	276.48	.....
40	L	404.0	1.091	.9163	409.77	409.36	130.47	.749
	R	403.9	.....	.....	409.65	409.25	130.40	.....
50	L	348.6	1.099	.9102	251.68	251.41	69.14	1.446
	R	348.8	.....	.....	251.60	251.33	69.16	.....
60	L	332.8	1.106	.9040	154.14	153.95	40.42	2.474
	R	333.0	.....	.....	154.04	153.86	40.42	.....
70	L	442.2	1.114	.8978	72.85	72.78	25.40	3.934
	R	442.5	.....	.....	72.79	72.71	25.38	.....
80	L	446.6	1.122	.8913	48.13	48.08	16.94	5.901
	R	448.4	.....	.....	47.99	47.95	16.96	.....
90	L	487.6	1.130	.8848	31.03	30.99	11.92	8.384
	R	490.7	.....	.....	30.86	30.82	11.93	.....
100	L	360.4	1.139	.8783	31.08	31.05	8.83	11.297
	R	365.9	.....	.....	30.79	30.74	8.87	.....

NOTE.—P_o is the true average pressure producing the flow and, of this pressure, the part P is used up solely in overcoming the viscous resistance. Cf. B. S. Bull., 14, p. 70; 1917.

TABLE 5.—Fluidities of Several Oils—Continued

LARD OIL

[Stearin crystallizes out at low temperatures. The effect of heating the oil is shown by the marked change in fluidity after cooling to 50 and 20° C.]

Temperature in degrees centigrade	Limb of viscometer	Time in seconds	Specific volume	Density	P_o	P	Viscosity	Fluidity
			cm^3/g	g/cm^3	g/cm^2	g/cm^2		
20	L	391.5	1.096	0.9126	266.99	266.98	82.38	1.214
	R	391.6	.....	.....	266.89	266.88	82.37	.....
30	L	405.0	1.104	.9058	165.89	165.88	52.96	1.890
	R	405.0	.....	.....	165.76	165.75	52.91	.....
40	L	509.3	1.112	.8933	89.00	88.99	35.72	2.780
	R	510.1	.....	.....	88.89	88.88	35.73	.....
50	L	457.7	1.120	.8926	70.13	70.12	25.29	3.955
	R	458.4	.....	.....	69.99	69.98	25.28	.....
60	L	495.6	1.129	.8861	47.79	47.78	18.66	5.354
	R	497.6	.....	.....	47.67	47.66	18.69	.....
70	L	377.8	1.137	.8794	47.78	47.77	14.22	7.028
	R	379.0	.....	.....	47.66	47.65	14.23	.....
80	L	426.0	1.146	.8726	33.24	33.23	11.16	8.953
	R	428.6	.....	.....	33.12	33.11	11.18	.....
90	L	409.0	1.155	.8657	27.79	27.78	8.98	11.17
	R	410.7	.....	.....	27.66	27.65	8.95	.....
100	L	335.0	1.165	.8586	27.79	27.78	7.33	13.62
	R	337.2	.....	.....	27.67	27.66	7.35	.....
50	L	506.2	.....	.....	64.99	64.98	25.92	3.855
	R	508.0	.....	.....	64.86	64.85	25.96	.....
20	L	520.7	.....	.....	210.40	210.39	86.34	1.157
	R	521.7	.....	.....	210.31	210.30	86.46	.....

Each of the fixed oils here tested has a considerably higher specific heat than does the single mineral oil, which may probably be taken as typical. Even at that the highest specific heat is a little less than one-half that of water.

The fluidities of the two fixed oils are generally greater (Fig. 5) than the fluidities of the mineral oil at the same temperature. The characteristic feature, however, is that the increase of the fluidity with the temperature is so much greater with the mineral oil. The contrast between the two classes of oils is brought out much more clearly when we plot the fluidities against the specific volumes, Fig. 6. The viscosities in centipoises are plotted in Fig. 7. Only a small portion of the curve for the mineral oil can be shown on the plot.

Although the specific heat and the slower change of fluidity with the temperature are both in favor of the fixed oils, we have tried to show that the adhesion is probably the main reason for the superiority of the fixed oils as *lubricants*.

G. Q. Lewis of the U. S. Navy Yard at Washington has made an elaborate study of the cutting properties of fixed oils, compounded

oils, and trade preparations. He employed for the tests the actual machines and materials which are to be used in practice. He has found several trade preparations to be superior to even lard oil in boring chrome nickel steel propeller shafts with an elastic limit of 100 000 lbs./in.^{2}. He has secured an increase of production of 50 to 100 per cent over the earlier practice, where a mixture of 10 per cent rapeseed oil and 90 per cent paraffin oil was used. A saving of 13 per cent in the cost of the oil was also obtained. One

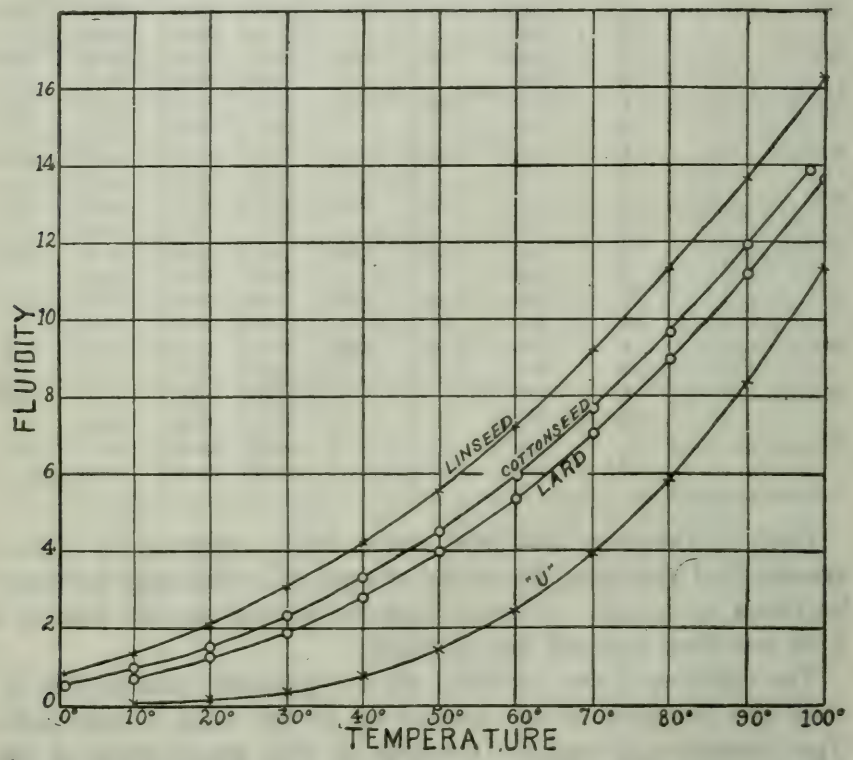

FIG. 5.—*The mineral oils increase in fluidity more rapidly with the temperature than do the fixed oils. A single asphalt-base oil "U" is here compared with lard, linseed, and cottonseed oils*

particular mixture increased production on a turret lathe 100 per cent; on small brass work it greatly increased the life of the tool and the cutting speeds; on a small lathe cutting gimble centers for torpedo gyroscopes from "Ketos" tool steel it doubled production and increased the life of the tool about 300 per cent. In an automatic screw machine, cutting alloy steel screws for securing air flask heads, a 1 to 6 mixture, costing 35.6 cents per gallon, gave results slightly better than those obtained with lard oil at $1.52

per gallon. When both oils were used under the same conditions, pieces cut from the same bar were smoother and therefore more desirable when the new preparation was employed. In the tool shop a 1 to 6 mixture at 35.6 cents per gallon, and later a 1 to 10 mixture at 29.2 cents per gallon, replaced sperm oil at $1.79 per gallon.

The results of numerous other tests are also given in the report. We merely add Fig. 8, which is an example of a graphical com-

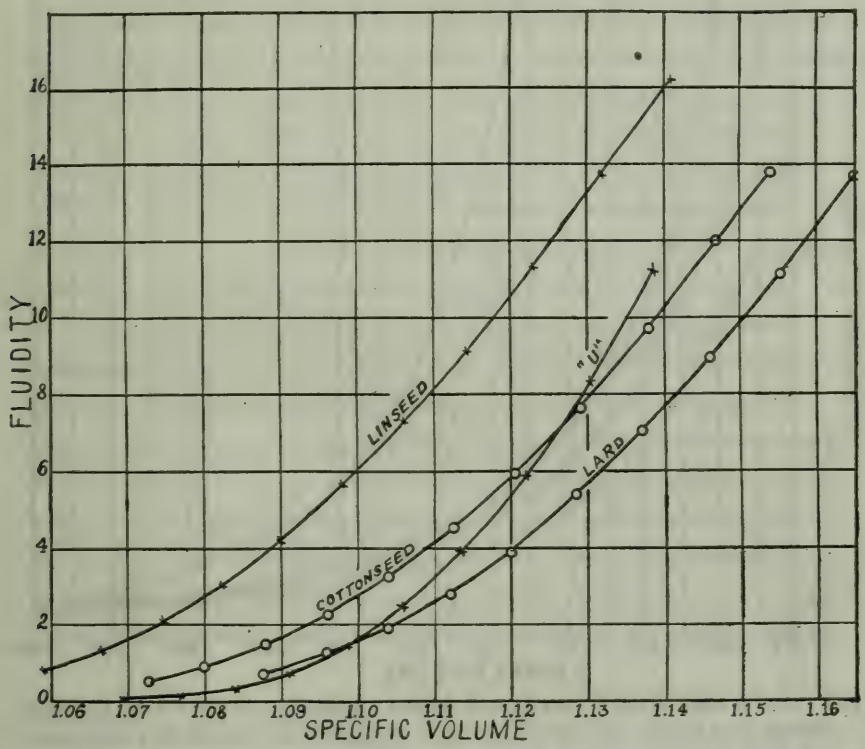

FIG. 6.—*The contrast between the mineral and fixed oils is most clearly brought out when the fluidity in absolute units is plotted against the specific volume in cubic centimeters per gram*

parison of different oils so diluted with paraffin oil that each of the mixtures would cost 35 cents per gallon. The machine was run by its own motor which was connected with an ammeter and voltmeter. The machine was run at a rate of 120 r. p. m. with a feed cut of 8 inches per hour on chrome nickel steel. The watts and the temperature of the oil were measured and were plotted against the elapsed time. With lard oil or pure mineral oil the tool would break down at once. With two of the mixtures tested, Nos. 13

and 18, the tool worked steadily without any balk whatever. With the other mixtures the machine balked and had to be started over again, as can be seen by the sharp maxima appearing in the curves. Mixture 13 is the one which had been found in the earlier tests to give such superior results. The temperature curves do

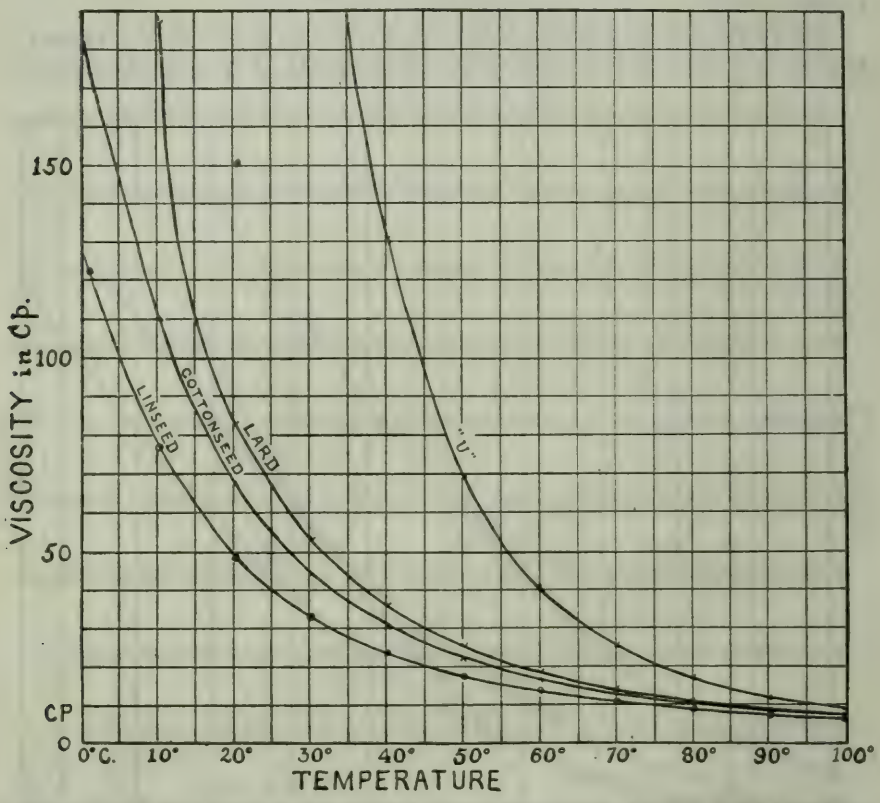

FIG. 7.—*It is more usual to plot vicosity against temperature, but due to the hyperbolic character of the curves, the figure would need to be more than tenfold its present height to show the complete curve for the mineral oil*

not seem to show any relation to the value of the oils, so they are not reproduced.

The author desired to test this oil on other operations. For this purpose a number of samples of oil were made up. A few of these were:

1. The preparation which had given best results at Navy Yard.
2. Lard oil.
3. A mixture of 90 per cent of paraffin oil and 10 per cent of oleic acid.

The oleic acid had been heated with sulphur.

4. Pine oil, sulphur, and turpentine.

These samples were placed in plain bottles with numbers only, sufficient dye and pyridine being added to the lard oil to disguise it. They were then given to a skilled mechanician to be used in threading wrought iron. The resulting threads were examined with a microscope by several independent observers. There was

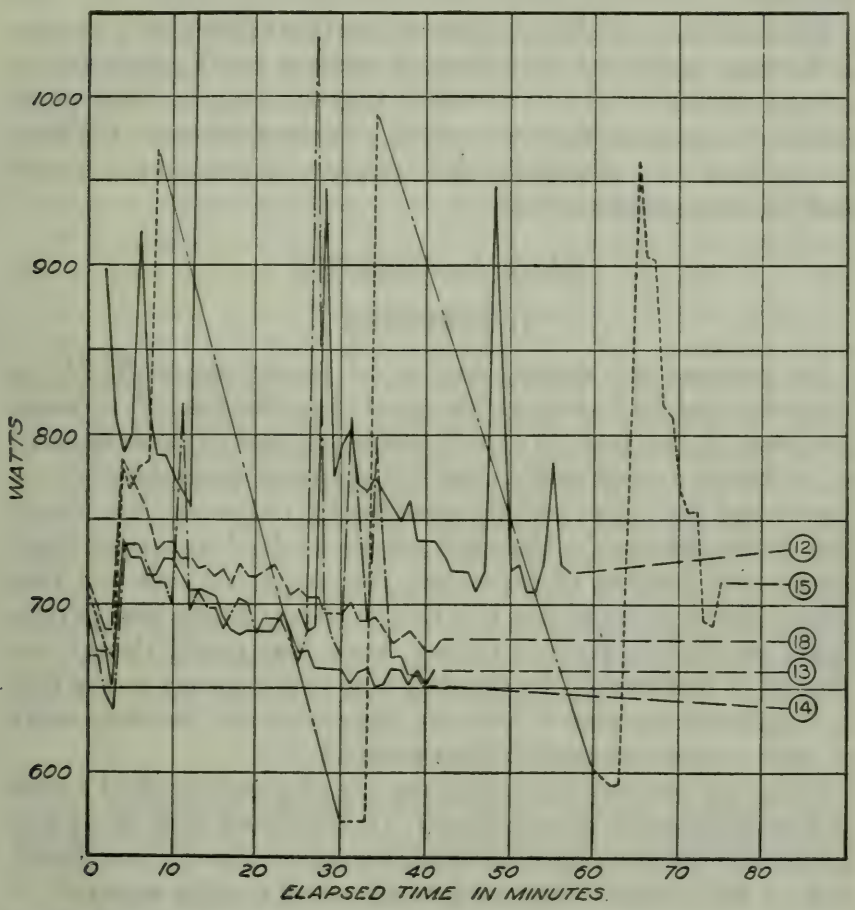

FIG. 8.—*Navy Yard tests showing fluctuations in power consumption when using various oils for lubrication.*

general agreement that the lard oil gave the best results and the new preparation, No. 1, the worst results. The results fell in the order, Nos. 2, 4, 3, 1. They were very decisive for this particular operation. Pure mineral oil was, of course, inferior to all of these.

It appears likely that lard oil is better than anything which has been devised for certain operations. It may be, however, that for

certain other operations, when a good lubricant is necessary, a substitute may do as well as or better than lard oil, and at a fraction of the cost. The prediction seems to be amply justified that oils with high residual affinity, such as those containing oleic acid, or pine oil with sulphur, will be found best. But it is noted that the trade preparation No. 1 also contained several per cent of sulphur.

So many persons have contributed to this bulletin in a variety of different ways that it is pleasant to have this opportunity to express thanks to all. It is hoped that bringing together these results of experience may not only be of practical benefit but that it may lead to a systematic investigation of the subject which shall be of far-reaching value.

PART 3.—PRACTICE

I. PURPOSES

The purpose of a cutting fluid is (*a*) to cool the work; (*b*) to lubricate, thereby increasing the speed of production; (*c*) to lessen the wear of the tool; (*d*) to diminish the energy consumption; (*e*) to insure a good finish; and (*f*) accurate dimensions; (*g*) to wash away the chips; and (*h*) occasionally to prevent the formation of metallic dust. Materials are often added to cutting fluids for the sole purpose of preventing the rusting or corrosion that would otherwise occur, but it is hardly correct to say that cutting fluids are used to prevent rusting, since that result, though important, is incidental. In the same way it is incorrect to say that cutting fluids are used to prevent disease merely because many of them contain germicidal substances.

There are two ways in which the use of a cutting fluid assists in getting accurate measurements: (1) The work may be unduly heated and thereby expanded unless a good cutting oil is employed, and (2) the "finish" obtained by such an oil is often essential.

Cooling is said to increase the cutting speed on wrought iron and steel from 30 to 40 per cent and on cast iron from 16 to 20 per cent. It is to be noted that the most effective cooling is obtained by directing the cooling fluid on the shaving at the point where it is being formed, because thereby, through cooling, the plastic flow of the material is lessened as well as the tendency of the shaving to seize on the tool. At the same time the fluid can be drawn in readily between the shaving and the tool, as the pressure fluctuates, and act as a lubricant.

Washing away the chips is quite important in such operations as deep drilling; for example, in the manufacture of rifle barrels. Securing a strong, continuous shaving is an advantage in such work and it is necessary to have a lubricant with sufficient adhesion. The stronger the force of the stream of cutting liquid the better it will carry away the chips, as well as cool and lubricate the parts. It sometimes happens that metallic particles are not carried away by the emulsions and they cause the dulling of the tool. This condition is avoided by using a stronger emulsion.

If the material is tough, a lubricant is necessary, but if brittle, it may be dispensed with. With cast iron, for example, no lubricant is necessary, but water in the form of an alkaline solution or emulsion may be used to cool the work, wash away the chips, and prevent the dust from getting into the air. The lubricant used in a given case will naturally depend upon the finish desired and the tolerances allowed. For roughing operations on a given material a cheap lubricant may suffice, whereas for fine operations on the same material, such as in the manufacture of micrometer screws, the best grade of lubricant is demanded regardless of price. There is the further fact that with some machines such as turret lathes and automatics, the cutting fluid and the oil used to lubricate the machine are liable to intermingle. In such cases an emulsion which would be serviceable as a cutting fluid would be worthless as a lubricant in the machine. It is perhaps needless to add that a cutting liquid must be used which will also serve to lubricate the machine.

II. SUBSTANCES USED

The substances used as cutting fluids may be classified under the heads (*a*) oils, (*b*) air, (*c*) aqueous solutions, and (*d*) emulsions.

1. OILS

We may subdivide the oils used into fixed oils, mineral oils, and compounded oils.

(*a*) Fixed Oils.—The fixed oils may again be subdivided into animal oils, fish oils, and vegetable oils.

Animal Oils.—Under animal oils we have the several varieties of lard oil, No. 2, No. 1, extra No. 1, and winter strained prime, tallow oil, neat's-foot oil, sperm oil, wool fat, horse oil, and whale

oil. Lard oil is the cutting oil *par excellence*. It is used on the most difficult work such as cutting delicate threads, tapping and cutting gears, deep hole drilling in steel and forming work such as the making of handles and balls on the turret lathe. It is not suitable for cutting very hard steel and glass, or where the heat production is excessive. Although lard oil does not vaporize, it carbonizes and gives rise to offensive odors. Small amounts of free acid present in the oil are probably beneficial and they do not cause corrosion of brass parts. There should, however, be not more than 15 per cent of free acid, as an excess of acidity will cause gumming and the formation of verdigris. In the great majority of cases substitutes for lard oil can be used to advantage.

The very high cost of the fixed oils as a class makes it desirable that the purchaser make suitable tests to determine that the material is both unadulterated and sanitary. Horse oil, in particular, seems to have been severely criticized from a sanitary point of view, but this is perhaps unwarranted.

Not only should the free acid be not too high, but the stearin should be kept as low as possible. During the winter months the lubricant stands in relatively cold shops overnight or over week ends, and if stearin separates out to any material extent, the oil is practically inoperative and means must be provided for heating it considerably above ordinary room temperature until the stearin goes back into solution.

Sperm oil is practically interchangeable with lard oil as a cutting oil, in spite of the fact that it does not resemble it in chemical composition and that it has a much higher fluidity.

Fish Oils.—Several users have experimented with fish oils. The report is that the results were satisfactory but the odor was so objectionable that their use was abandoned. Fish oils, however, can be deodorized, and it is understood that these deodorized oils are already available. Whale oil has been abandoned on account of its odor, but otherwise it would be satisfactory.

Vegetable Oils.—Under vegetable oils, olive oil, rapeseed oil, mustard-seed oil, castor oil, peanut oil, soya-bean oil, cocoanut oil, cottonseed oil, corn oil, and linseed oil have been more or less extensively used. Under the heading of vegetable oils we may also include creosote oil, turpentine oil, turpentine, pine oil, and rosin oil, although they are distillates and therefore are not "fixed oils."

From the iodine numbers of these oils it can be seen that the tendency to oxidize and, therefore, to gum is very great in linseed oil, and it is moderate in some of the other oils such as cotton seed. The tendency of the oil to give trouble by gumming, and the fire hazard as well, can be reduced by diluting it with mineral oil.

In continuous use it is obvious that all cutting oils will become contaminated. They should be sterilized frequently by heating, all solid particles should be given an opportunity to settle out, and after a certain time the whole system should be cleaned out and the oil purified or replaced.

The objection to the fixed oil on account of expense does not apply to the distilled oils of vegetable origin. The tendency of pine oil to produce a foam is objectionable, but when this oil is compounded with sulphur and a mineral oil this tendency is reduced. These oils appear not to be very widely used except in emulsions, where rosin oil and soluble creosote are apt to cause foaming. They come to the top, adhere to the chips, and frequently choke up the system.

Cottonseed oil is much used in the South, but many have rejected it, owing to its gumming. It is suggested that there are many operations, such as threading and tapping by hand, where cottonseed oil could be used either alone or in mixtures. But it will not do in place of lard oil for very fine work. Corn oil has been suggested for use on account of its low cold test.

The use of white lead and linseed oil in tapping and threading by hand seems to be very common. A number of other solids are used to a greater or less extent. Graphite, sulphur, and ground mica are examples.

In drawing fine lead wires cold it is creditably reported that palm oil, which contains free palmitic acid, works perfectly, whereas vaseline of almost identical consistency is no good. If the metal is drawn warm enough, beef tallow, which contains stearic acid, works well, but paraffin is not good. This is evidence of the effect of adhesion.

Turpentine is very useful for certain classes of work, as in cutting aluminum, very hard steel, and glass. But the fire hazard is great with its use. It is often compounded with lard oil. By itself it is too fluid to act as a lubricant. It is recommended where lard oil causes a "glaze."

(*b*) MINERAL OILS.—The mineral oils are naturally cheaper than the fixed oils. In fluidity they range from kerosene, which is used in cutting brass and aluminum, to heavy engine oils. They prevent rusting and are very stable, so that corrosion, carbonization, and gumming are small factors. They are not cheap enough to compete with emulsions on the one hand; and on the other hand, because they do not have sufficient adhesion to those steels which are difficult to work with emulsions, their use is not very satisfactory. On aluminum, kerosene is preferable from every point of view to a fixed oil. On brass, a paraffin oil of 25 to 28° Baumé mixed with 5 per cent of 300° fire-test kerosene is described as ideal. On these metals many use no cutting fluid whatever. On account of the fire hazard emulsions might better be used.

(*c*) COMPOUNDED OILS.—Compounded oils are the natural result of the desire to secure the adhesion of the fixed oils combined with the stability and cheapness of the mineral oil. Thus compounded oils are being supplied under a great variety of trade names, many of which suggest the presence of lard oil. Some of the compounded oils actually do contain considerable amounts of lard oil, while others contain none at all. A typical formula may be given as follows:

	Per cent
Lard oil	25
Corn oil	15
Natural West Virginia petroleum	60

Many users state that fixed oil must be present to the extent of from 10 to 50 per cent, and that thereby the valuable advantages of lard oil are gained in full measure. On the other hand, for some classes of work there is abundant testimony that even 50 per cent of lard oil is not sufficient. One large user testifies that 10 per cent of rapeseed oil added to a paraffin oil caused a positive loss in cutting value.

It should be observed that "cutting compounds," which are very satisfactory to many large users, apparently contain no fixed oil whatever. Thus there is possible a great saving in fats by a knowledge of the best usage in regard to cutting oils. It appears probable that the necessary adhesion can be gained by thoroughly incorporating sulphur in oils, such as red oil (oleic acid) and pine oil, which themselves have considerable adhesion. It will not do, however, to have the sulphur merely in coarse suspension, as it will settle out. It should be chemically united.

2. AIR

Air can not be considered as a lubricant for the purposes which we are here discussing, and it has very little cooling effect. However, with a brittle metal like cast iron it is used successfully to take away the chips, and thus it prevents the loading and choking of the tools. The flying of the chips makes guards necessary, and the dust is also an inconvenience.

3. AQUEOUS SOLUTIONS

Water alone has been found satisfactory in some cases, as in the drilling of ship plates and boiler plates. Water does not generally give a smooth finish, nevertheless it is sometimes used to give a bright, smooth surface to steel, which is called a "water-cut" surface. It may also be used on brass and aluminum, but water is in disfavor, owing to the fact, noted by every machinist, that it rusts the machines and the work as well if this is either iron or steel.

To prevent rusting, an alkali may be added to water. Thus for some operations, such as grinding and drilling, a 1 to 2 per cent solution of sodium carbonate has been found satisfactory. Caustic soda, borax, sodium silicate, and sodium resinate are all used.

A soluble soap is added with the same end in view. Thus a solution of 50 pounds of sodium carbonate and 25 pounds of soft soap in 200 gallons of water is said to have given satisfactory results in boring deep holes, as in gun tubes. Soap, moreover, has the advantage that if oil is added it will readily form an emulsion which will possess the cooling properties of water and will lubricate better than water, either alone or containing soda or soap. Soap solutions have the disadvantage that as the water evaporates they become sticky and may clog the feed pipes, etc.

4. EMULSIONS

There are three types of material used for making emulsions:

1. One class of "soluble oil" is made from mineral oil compounded with a neutralized sulphonated oil. The fixed oils when treated with sulphuric acid unite with the acid to form so-called sulphonic acids, which after neutralization with alkali are readily soluble in water. Rosin oil, though a less valuable product, is sometimes used. The mixture with mineral oil is, of course, not soluble in the strict sense, but it does emulsify in the heated solution.

2. The second type of soluble oil is made from a mineral oil compounded with an alcoholic solution of soap. Potassium or "soft" soap is preferred. Both of these are marketed as clear oils. In use the oil is stirred into water, usually 1 part of oil to 4 parts of water.

3. The third variant is marketed as paste made of a thick soap solution and mineral oil. These are known as cutting pastes or compounds.

Of the three forms the last is the least desirable, and the second is perhaps the most so, as it may be made without expensive apparatus and requires much less technical skill to fabricate. The chances of its being made properly are therefore greater. One very large user has developed the following formula, which is reported to give very satisfactory results and may be taken as typical:

	Gallons	Per cent
Water	2.00	6.0
Alcohol	1.50	4.5
Caustic solution (30° B)	.75	2.0
Kerosene	6.00	17.5
Oleic acid	3.00	9.0
Machine oil	21.00	61.0
Total	34.25	100.0

This amount of soluble oil is then diluted to make 860 gallons for average work. Another typical formula is made up as follows:

	Per cent
Caustic soda	0.65
Alcohol and water	5.8
Resin acid	1.64
Fatty acids	11.76
Mineral oil (22.5° B)	80.15

Such an oil is diluted with water according to the kind of metal to be machined or the character of the operation. In a dilution of one to three parts of water, it is said to do the same work under any and all conditions that is required of pure lard oil. It should be observed that neither of these formulas contains either a fixed oil or a disinfectant. Soluble oils will take care of the most difficult as well as the lightest work at a far less cost for the same treatment than any other cutting lubricant. They are particularly recommended where the heating is excessive. The emulsion must be exceedingly fine grained, so that it will penetrate readily and not tend to settle out. Emulsions give trouble on automatics or machines with turret heads because the emulsion gets under the

turret and displaces the lubricant. In this case the turret will stick and the machine has to be taken apart and cleaned. If the operator will frequently squirt lubricating oil through the turret, it will tend to obviate the difficulty.

In filtering through a column of chips, as in a deep bore hole, it has been repeatedly noticed that the character of the emulsion becomes changed. Presumably the oil is held back and the lubricating property of the emulsion is lost. The very virtue of an emulsion, that its composition can be readily changed to suit conditions, is thus a disadvantage, since it is also continually changing during use. Thus, the system must be watched and occasionally it should be thoroughly cleaned out and a new emulsion put in. This should be done anyway, from sanitary reasons. The oil can be recovered by the use of a rotary separator.

Some waters are sufficiently hard or salty in character to render an emulsion unstable. Strong acids are, of course, destructive to emulsions in even exceedingly small amounts. If the water of the locality is suspected of causing instability of the emulsion, rain water may be tried, and if this removes the difficulty, it may be found possible to soften the water. In making an emulsion it is well to follow the exact procedure which has been found to be successful. Too much mineral oil in the emulsion is a cause of instability. Ammonia is often present in soluble oils but it is not to be recommended, since it will tend to make an unstable emulsion and to promote corrosion.

Gum arabic and starch are sometimes added to cutting oils, presumably in order to increase the stability of the emulsion. Phenol and cresol are frequently used because they give the mixture a distinctive odor and render it less habitable by disease-producing bacteria. The use of phenol, even in the form of its salts, is objected to, and it would appear that recently developed disinfectants are far less likely to be injurious to the workmen and are at the same time better germicides.

III. OPERATIONS AND MACHINES

The character of the operations performed, the shape and adjustment of the tool, the speed, feed, and depth of cut have more to do with the choice of a cutting fluid than the character of the steel. It is therefore feasible for the management to predict beforehand the most suitable lubricant and save time and materials. For the

great majority of operations aqueous solutions and emulsions made up of suitable strengths over quite a wide range should undoubtedly be used.

For drilling, an emulsion (say, 1:20) is most commonly used, but for light, slow work a compounded oil, or even lard oil, is resorted to. For rough drilling, water containing a little soda, soap, or borax is employed. Much soda will give rise to foaming.

For reaming, an emulsion (1:3) is generally used, although the work is often done dry. For a high polish and for extremely heavy work, compounded oil or lard oil is resorted to.

For milling, emulsions (1:20) are almost universally used, with alkaline solutions, compounded oils, and lard oil as variants. Planing is often done dry. Sometimes a lubricant is applied with a brush. In many cases, however, an alkaline solution or a dilute emulsion (1:20) is used, especially if a high polish is desired.

In tapping and threading, emulsions are not so often successful as in the above cases, but they are used nevertheless in a large minority of instances. Lard oil and compounded oils are resorted to generally, with or without the addition of white lead to prevent the binding of the taps and dies and to secure a smooth, steam-tight finish.

Turning practice in different shops and for different operations shows the widest variance. Some workmen turn dry, others with alkaline solutions, emulsions, compounded oils, corn oil and—where a high finish is desired—lard oil and turpentine.

On automatic screw-cutting machines and machines with a turret head it is best to use a compounded oil with as small a proportion of fixed oil as will serve the desired ends.

IV. MATERIALS

The nature of the material should be taken into account in determining the most suitable oil. There is a consensus of opinion that soft steel and wrought iron are difficult metals on which to get a good surface without the use of lard or sperm oils. Some of this difficulty can be overcome by the shape of the tool, one with more rake being required for the soft metals. A change of speed or feed also helps at times. Without suggesting a cause, we may be permitted to merely report the fact that speeding up the operation has often decreased the number of failures from "bugging" and also the excessive wear on the tools. In threading wrought iron in dies it is almost impossible to get a good thread

without the use of lard oil or sperm oil. In drilling deep holes in tough steels at high speed of production, as in making rifle barrels, lard oil or its equivalent is positively necessary. Of course, it is possible that pine oil united with sulphur and compounded with a suitable mineral oil will in time replace lard oil, which is needed for other things.

Lard oil or some oil with good adhesion will be used where a long chip is obtained, and it will not be needed where the chips are short, which indicates a brittle material. In the latter case, cooling is the more important function of the cutting oil.

With a very hard, brittle steel, turpentine is called for, to cause the tool to "bite," since lard oil would merely produce a glaze.

Forming tools sometimes have a tendency to "hog" the metal, which is an indication that a better lubricant is required. It must be remembered that a very thin film of good oil is often sufficient to give the smooth surface that is desired, whereas it can not be obtained by the use of a flood of water or other substitute.

V. FORMULAS

It is advisable for the engineer of tests in each large organization to give careful study to the subject of cutting oils rather than accept too readily the customary substitutes supplied by the trade. Of the several hundred materials on the market some are good while others are positively harmful. Small concerns buy up odd lots of oil where they can be obtained cheaply, but they are not always able to keep their products uniform. The freight rates to and from their plants have to be added to their costs. It is, after all, not difficult to manufacture a cutting oil, but it is difficult to analyze a compounded oil so as to be able to state with certainty whether it is constant in composition and whether the components are healthful and pure. Moreover, the user can, by studying his own needs, change his formulas until he finds that his needs are being met in the most economical manner.

The number of formulas required by a large works need not be very great. The practice of a single concern, taken as typical, may be given in detail:

1. *Pure Oils.*—(*a*) Pure lard oil, off prime, free fatty acids, determined as oleic acid not over 5 per cent. Restricted to cutting nickel steel and other steel of high cutting hardness. Its delivery is controlled under rather rigid restrictions.

(*b*) Pure mineral spindle oil, viscosity 100 seconds, Saybolt Universal at 40° C, flash point in open cup, 185° C. Used in many classes of work, both in automatic machines and on turret lathes and on other machines where a light-bodied oil is

adapted. It is used in turning, shaping, and cutting both steel and copper and in all operations on brads in automatic machines.

2. *Compound Oils.*—(*a*) Equal parts of lard oil and mineral spindle oil. Used generally on automatic machines and on other lathes in heavier classes of work for processes which include tapping and threading. It is also used on machines which are changed frequently from operations for which the pure mineral spindle oil would be used to operations involving tapping and threading for which the lard-oil mixture is required.

(*b*) Equal parts of mineral spindle oil and heavy mineral oil, viscosity of the latter 730 seconds, Saybolt Universal at 40° C, flash point, 205–210° C. This mixture is substituted for the spindle-lard-oil mixture wherever practical experience shows that it is economically possible.

3. *Water Compounds.*—(*a*) Solution of water and soda. Used in turning of large shaft forgings.

(*b*) Solution of soap and water. Used on simple milling and drilling operations where a water lubricant of light body is satisfactory.

(*c*) Emulsion of water, soap base, soda, and lard oil. Used where a water lubricant of good body is required. It is generally in use on boring mills, Gisholt lathes, cold cutting-off saws, milling machines, etc., and in the cutting of metals in general.

(*d*) Emulsion of water, soap base, soda, lard oil, and mineral spindle oil. Used solely for the grinding and finishing of small steel shafts.

The above table gives a clear idea of the number of cutting fluids which are deemed necessary to meet all the needs of a large plant, but obviously the amounts of the different fluids which are required will be very different. It is interesting to note the experience of a large manufacturer on this point. He finds that a pure paraffin oil (25° Be) can be used for 98 per cent of the work requiring a cutting oil. For the large portion of the remainder he uses 40 per cent of off-prime lard oil or sperm oil compounded with 60 per cent of paraffin oil (25° Be). For only a very small portion of the work he uses off-prime lard oil or sperm oil.

VI. APPLICATION OF THE FLUID

Taylor[27] seems to have been the first to recognize the very great gain in cutting speed which can be made by having the cutting fluid applied in a heavy stream with as much force as practicable directly upon the chip. From what has already been said it is obvious why this should be so. It has been noticed that many of the machines work better in winter than in summer, which can be explained by the more effective action of the cooling fluids. With the better lubricants, such as lard oil, it is probable that no corresponding gain would be obtained by the use of a heavy stream even if it were practicable.

The use of white lead combined with the oil used in threading and tapping is readily justifiable. By itself the oil would quickly

[27] Art of Cutting Metals, p. 11.

run off, but by adding a finely divided solid the fluidity of the mixture is lowered and it "stays put." If white lead were objected to on account of the danger of poisoning, it could probably be replaced by zinc oxide or deflocculated graphite. Unfortunately, workmen find graphite objectionable on account of the color.

VII. KIND OF CUTS

Where the heating is necessarily very great, an emulsion is always to be preferred. If for some reason a better lubricant seems required, one would naturally suppose that the lighter the cut the less viscous the oil need be, and, conversely, with a deep cut one might expect to have to use an oil with high viscosity. This, however, is not the case, for if the viscosity of the oil is high it will be slow in reaching the surfaces to be lubricated and the cooling effect of the oil will also be reduced. Hence, an oil of low viscosity is preferred for all high-speed work. To emphasize the importance of cooling, it may be said that in milling the teeth of steel gears, the thinnest soap solution that can be used without rusting the machine will do better work than pure lard oil. In using pure lard oil for this purpose, the friction of the tool is so great as to burn the oil and fill the room with smoke. The life of the cutters is no longer with pure lard oil than when a water compound is used.

VIII. HYGIENIC ASPECTS

The used oil contains sharp metallic particles which are sufficiently small to enter the hair follicles of the skin. If not washed out, they may block up the openings to the sebaceous glands, produce irritation and abrasions, and therefore a favorable environment for pus-forming bacteria. The oil itself should not produce any irritation to the skin, but it is suited to catch germs which are floating about and retain them. The clothing has this same tendency where it becomes moistened with the cutting fluid. The main precautions to be taken are (1) the removal of the fine particles of metal from the used oil, particularly those which are less than 0.04 mm in diameter; (2) cleanliness on the part of the workmen, with abundant facilities therefor, also preventing the cutting fluid from coming into contact with the clothes and person more than is necessary; and (3) the avoidance of the use of strong acids in sulphonated oils or from the pickling liquor and too great

an excess of fatty acids or of alkali, or the use of irritating antiseptics, etc., in the composition of the oils.

The metallic particles can best be removed by settling in a large tank. This is easier to accomplish if the oil is not too viscous and therefore if the oil is hot. It may be cleared by filtration or by means of a centrifugal separator.

It is an excellent practice to have available in the wash room a soap emulsion of a light petroleum oil to rub on the hands and arms before using the soap and brush. This makes the greasy layer more fluid and thereby facilitates its removal by means of soap and water.

The United States Public Health Service is making a study of the hygienic aspect of cutting fluids, hence a more detailed discussion of the subject would be out of place here.

WASHINGTON, April 20, 1921.

DEPARTMENT OF COMMERCE

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TENSILE PROPERTIES OF SOME STRUCTURAL ALLOY STEELS AT HIGH TEMPERATURES

By H. J. French

ABSTRACT

The report gives results of determination of tensile strength, proportional limit, elongation, reduction of area, and strength at fracture throughout the range 20 to 550° C for four steels containing about 0.38 per cent carbon, as follows: (*a*) Plain carbon steel; (*b*) 3½ per cent nickel steel; (*c*) 3 per cent nickel, 1 per cent chromium steel; (*d*) 1 per cent chromium, 0.20 per cent vanadium steel.

Brief reference is made to the type of fractures obtained in testing steels at various temperatures, and particular attention is paid to comparison of the tensile properties of these alloys at 550° C.

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I. INTRODUCTION

In the attempted production of ammonia in the United States by the Haber process[1] gradual elongation and ultimate fracture of bolts in converter chamber heads have introduced serious operating difficulties. Under a mean temperature of 550° C to which heads, nuts, and bolts were subjected the elongation of the latter was such as to require tightening of the nuts almost daily. The use of some of the more commonly employed structural alloy steels did not remove this difficulty, and a search of the literature revealed little exact information on which a comparison of the high temperature tensile properties of various alloy steels could be based.

In view of the fact that an investigation of the resistance to corrosion by ammonia of various ferrous and nonferrous alloys

[1] R. S. Tour, "The direct synthetic ammonia process," Journ. Ind. and Eng. Chem., 12, No. 9, p. 844; September, 1920.

was in progress in connection with redesign of operating equipment by the Ordnance Department, the Bureau of Standards was requested to undertake determination of the tensile properties of a number of structural alloy steels throughout the temperature range 20 to 550° C (70 to 1020° F). From the combined results of investigation of resistance to corrosion of various metals and the tensile properties of steels at high temperatures it was hoped that selection of a suitable alloy for withstanding required stresses could be made, and if this proved unsatisfactory as regards resistance to attack by the gases encountered at least a more suitable metal lining for the converters could be installed.

The original plan of procedure included tests of a plain carbon steel and a number of structural alloy steels, most of which were of acknowledged industrial importance. However, because of the desire to keep variations in carbon content at a minimum, difficulty was encountered in obtaining some of the alloys, notably carbon-manganese and chromium-molybdenum steels, of the exact composition desired, so that this report comprises only tests of four steels.

It is further restricted to tests of these alloys in a normalized condition, as data so obtained form a basis of comparison with tests of samples first subjected to quenching and tempering. The high operating temperatures attained, which reach about 650° C (1200° F), limit the tempering subsequent to hardening to relatively high temperatures, while the large dimensions of the converter heads and some of the other parts of the equipment subjected to high temperatures, which would introduce difficulties in quenching, make the use of a forged or normalized steel highly desirable.

Shortly after completion of the tests about to be described tensile properties at high temperatures of a number of carbon and alloy steels subjected to varying thermal treatments were reported by MacPherran,[2] and in discussion of this paper by Spooner considerable additional data were presented. However, the work of MacPherran and Spooner was confined, in so far as the elastic properties are concerned, to determination of yield point; whereas the tests carried out by the present author include determinations of the limit of proportionality and strength at fracture, and the interpretation of these data is somewhat different from that given by either of the authors mentioned.

[2] R. S. MacPherran, "Comparative tests of steels at high temperatures," Proc. Amer. Soc. for Testing Materials; 1921.

II. PREVIOUS INVESTIGATIONS

As already indicated, there was until quite recently a scarcity of accurate data on the high temperature tensile properties of various structural alloy steels. This is still the case as regards the effect of temperature on the limit of proportionality, of importance in design of engineering equipment, and in addition there is some disagreement between results reported by different investigators for similar alloys. Bregowsky and Spring[3] determined yield point, tensile strength, elongation, and reduction of area from 20 to 550° C (70 to 1020° F) for rolled 30 per cent nickel steel.

In 1913 Schulz[4] reviewed available data relating to the high temperature properties of turbine materials, but the information presented for alloy steels was, in large part, for those containing varying proportions of nickel.

Guillet[5] reported, among several special alloys for use at high temperatures, a steel containing nickel, chromium, and tungsten which showed exceptionally high strength at 750 to 800° C (1380 to 1470° F).

A comprehensive analysis of the effects of high temperatures on hardness, tensile and impact properties, freedom from warpage, etc., of steels containing 3 per cent nickel and various proportions of chromium, high-speed steels and various chromium and chromium-cobalt steels was recently prepared by Gabriel.[6] As regards high tensile strength at elevated temperatures, these steels were considered of value in the following order: (1) High tungsten; (2) high chromium, high carbon; (3) high chromium, low carbon; (4) 3 per cent nickel and nickel-chromium.

In the selection of steels for valves the author recommended the different type alloys, as follows: (1) A tungsten steel, (2) a steel high in chromium, (3) a nickel steel.

MacPherran[7] recently reported tensile tests from 20 to about 650° C (70 to 1200° F) for a variety of alloy steels under different heat treatments, as shown in Table 1. In discussion of this paper A. P. Spooner presented a large number of tests at temperatures up to about 870° C (1600° F) for the different steels listed in

[3] I. M. Bregowsky and L. W. Spring, "The effect of high temperature on the physical properties of some alloys," Proc. Int. Assoc. for Testing Materials, VI Congress, VII$_1$; 1912.

[4] Schulz, "Neuere versuche und erfahrungen mit turbinenschaufelmaterial für höhe temperaturen," Die Turbine, 9, p. 243; 1913.

[5] L. Guillet, "Alloys having remarkable properties at very high or very low temperatures," Rev. Met. 11, p. 969; 1914.

[6] G. Gabriel, "Comparative values of motor valve steels," Iron Age, 106, p. 1465; 1920.

[7] See note 2.

Table 2 and, in general, confirmed the work of MacPherran where direct comparisons were possible.

TABLE 1.—Alloy Steels Tested at High Temperatures [a]

Type composition (per cent)					Condition in which steel was tested
C	Mn	Ni	Cr	V	
0.21	.....	3.25	.....	.....	Annealed at 802° C (1475° F)
.25	.....	33.9	.....	.....	Do.
.34	.....	2.38	0.38	.....	816° C (1500° F) water, 705° C (1300° F)
.53	.....	20.78	7.42	.....	As rolled
.30	.....	.....	.83	0.17	857° C (1575° F) water, 732° C (1350° F)
.69	.....	.....	3.36	.....	843° C (1550° F) water, 705° C (1300° F)
.72	0.92	.....	.....	.....	Annealed at 802° C (1475° F)
.82	.....	.....	.91	.18	816° C (1500° F) water, 705° C (1500° F)

[a] MacPherran, Amer. Soc. for Testing Materials; 1921.

TABLE 2.—Alloy Steels Tested at High Temperatures [a]

Type composition (per cent)						Condition in which steel was tested
C	Ni	Cr	V	Mo	W	
0.10	.....	.....	.....	.....	.....	Normalized 870° C (1600° F)
.45	.....	.....	.....	.....	.....	Do.
.33	3.5	.....	.....	.....	.....	Do.
.38	2.0	1.0	.....	.....	.....	Do.
.37	.....	1.0	0.20	.....	.....	Do.
.47	.....	1.0	.....	0.35	.....	Do.
1.10	.....	.50	.20	.....	.....	Annealed 740° C (1360° F)
.48	.....	1.3	.20	.....	.....	Annealed 730° C (1350° F)
.25	.....	14.0	.....	.....	.....	Annealed 790° C (1450° F)
.66	.....	3.2	.70	.....	15.9	Annealed 905° C (1660° F)
.20	.....	31.0	.....	.....	.....	Annealed 760° C (1400° F)

[a] A. P. Spooner, Proc. Amer. Soc. for Testing Materials; 1921.

These data, while the most recently presented, are together the most comprehensive compilation of tests so far recorded for the modern types of structural alloy steels, but consist of determinations of tensile strength, elongation, reduction of area, and, in part of the temperature ranges given, values for yield point.

III. MATERIALS AND METHODS USED

The four steels tested were made by the electric furnace process at the plant of the Halcomb Steel Co., Syracuse, N. Y., and supplied through the Nitrate Division, Ordnance Department, in the form of 1 by ½ inch hot-rolled bars of the compositions shown in Table 3. After cutting into desired lengths for test specimens the bars were normalized by heating to 800 or 850° C (Table 3) and cooled in still air. They were then machined to the form and dimensions shown in Fig. 1. All tests were made with the special apparatus devised by the author and in the manner previously described[8] in detail.

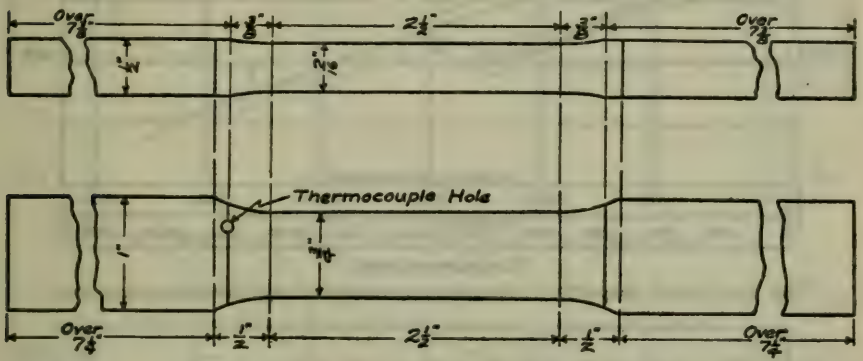

FIG. 1.—*Form and dimensions of test specimen used*

TABLE 3.—Composition and Heat Treatment of Steels Tested

Steel	Composition (per cent)								Heat treatment: Heated for 30 minutes at temperature designated and cooled in still air
	C	Mn	P	S	Si	Ni	Cr	V	
A.....	0.38	0.56	0.014	0.013	0.14	.....	.....	.....	850° C
B.....	.37	.67	.021	.010	.20	3.43	.....	.....	800° C
C.....	.39	.59	.019	.009	.23	3.05	0.93	.....	850° C
D.....	.37	.74	.020	.023	.21	.....	1.04	0.17	850° C

IV. EXPERIMENTAL RESULTS

1. TENSILE TESTS

(*a*) TENSILE STRENGTH.—The results of tensile tests at various temperatures throughout the range 20 to 550° C (70 to 1020° F) are given in Tables 4, 5, 6, and 7, and represented graphically in Figs. 2 to 5, inclusive.

[8] Forthcoming Bureau Tech. Paper: Effect of Temperature Deformation and Rate of Loading on the Tensile Properties of Low Carbon Steel Below the Thermal Critical Range. Also H. J. French, "Tensile properties of boiler plate at elevated temperatures," Min. and Met., 158, sec. 15; 1920.

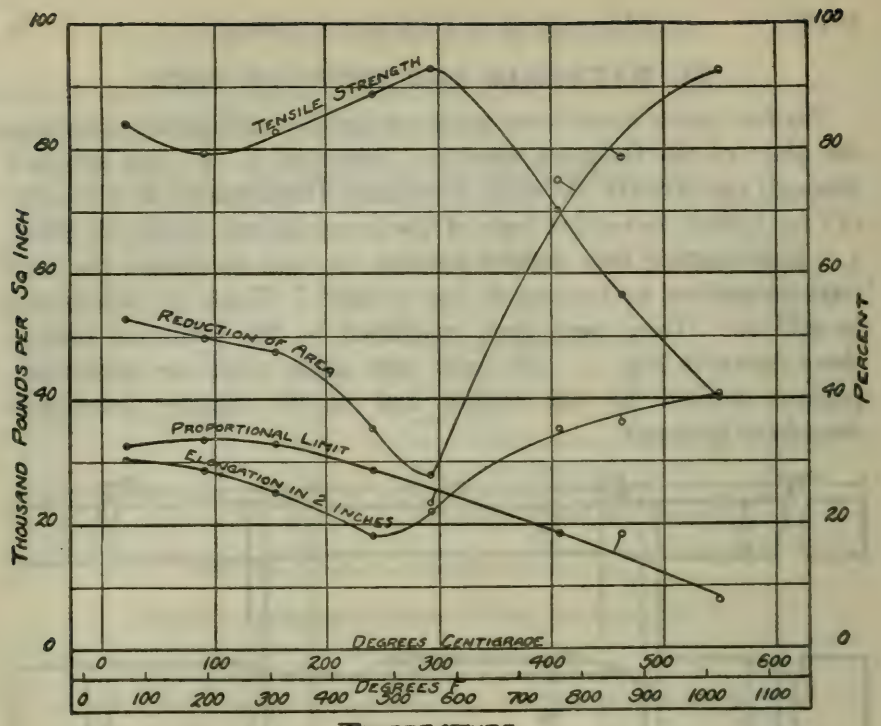

FIG. 2.—*Tensile properties at elevated temperatures of 0.38 per cent carbon steel*

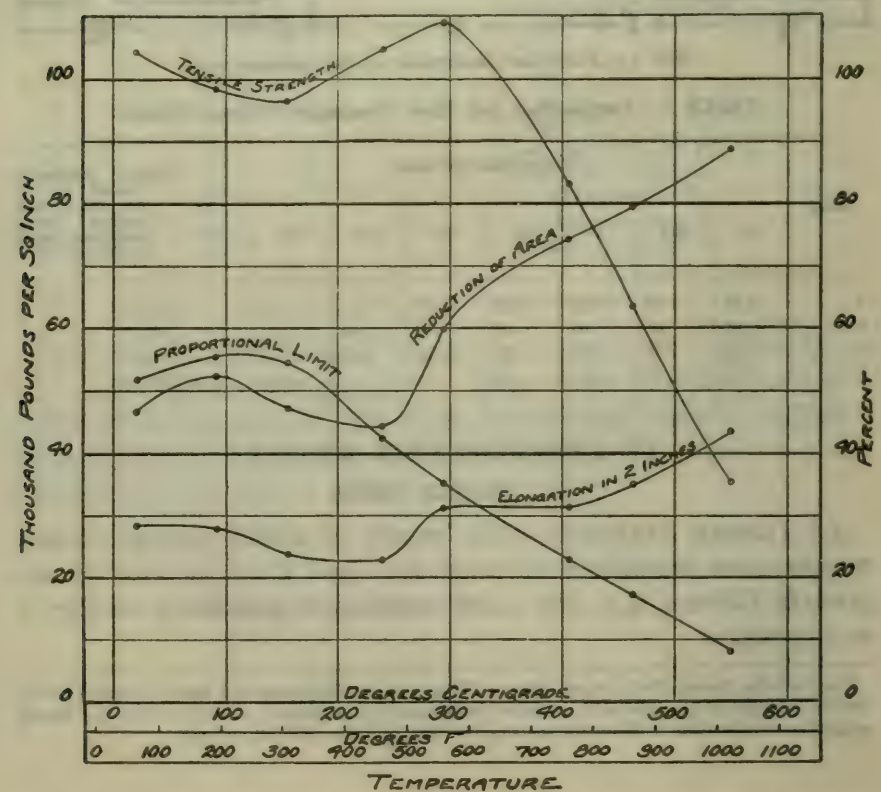

FIG. 3.—*Tensile properties at elevated temperatures of 3½ per cent nickel steel containing 0.37 per cent carbon*

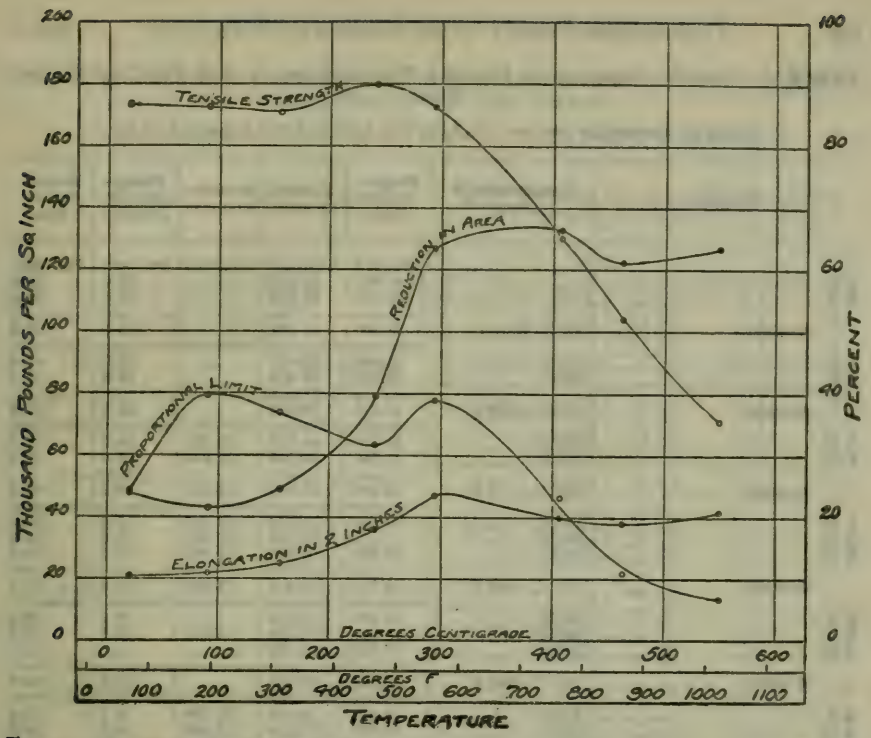

FIG. 4.—*Tensile properties at elevated temperatures of nickel-chromium steel o the type 3 per cent nickel, 1 per cent chromium, and 0.4 per cent carbon*

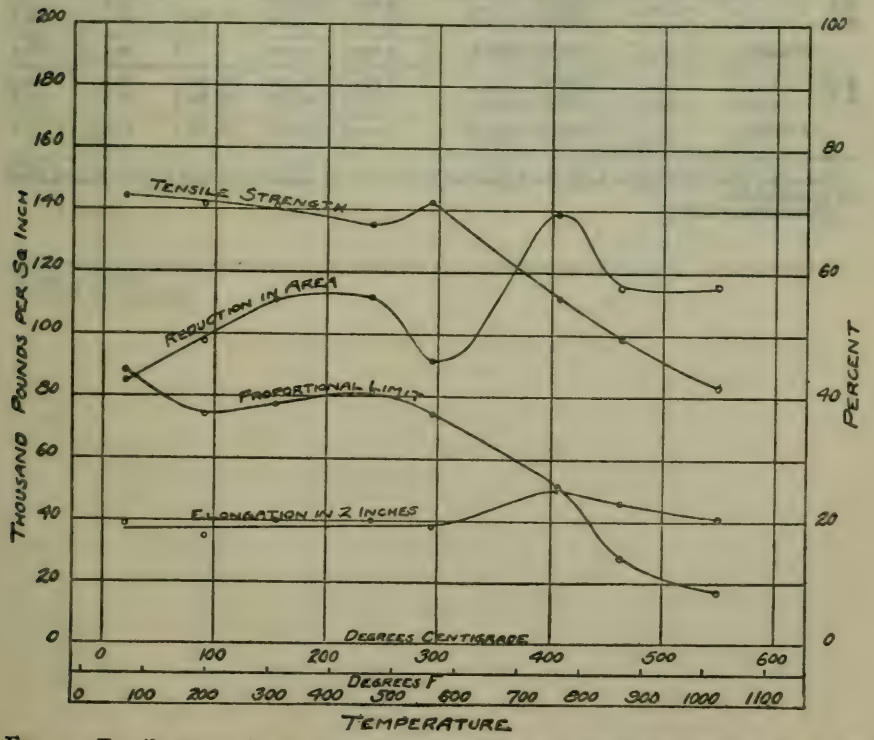

FIG. 5.—*Tensile properties at elevated temperatures of chromium-vanadium steel of the type 1 per cent chromium, 0.2 per cent vanadium, and 0.37 per cent carbon*

TABLE 4.—Tensile Properties at Elevated Temperatures of 0.38 Per Cent Carbon Steel

[Chemical composition (per cent): C, 0.38; Mn, 0.55; P, 0.014; S, 0.013; Si, 0.14]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
A-1	(b)	34 900	85 200	.....	27.5	52.3
A-2	(b)	30 500	83 200	.....	33.5	53.3
Average	21° C (70° F)	32 700	84 200	.....	30.5	52.8
A-6	92° C	34 000	79 400	.....	28.0	47.6
A-9	92° C	33 700	79 500	.....	29.5	52.2
Average	92° C (198° F)	33 850	79 450	.....	28.8	49.9
A-10	155° C	33 250	85 500	140 000	24.5	47.2
A-13	155° C	32 750	80 200	137 000	26.0	48.3
Average	155° C (311° F)	33 000	82 850	138 500	25.2	47.8
A-12	241° C	27 500	87 500	129 000	19.0	37.0
A-17	241° C	.....	90 400	127 400	18.0	32.7
A-18	241° C	30 000	88 900	129 700	17.5	36.9
Average	241° C (466° F)	28 750	88 950	128 700	18.2	35.5
A-8	292° C	26 000	91 500	.....	24.0	28.6
A-11	294° C	24 500	93 500	116 700	20.0	27.5
A-19	294° C	20 000	94 000	.....	.....	.....
Average	293° C (559° F)	23 500	93 000	.....	22.0	28.0
A-7	407° C	18 500	68 000	137 700	36.5	76.2
A-15	407° C	18 500	72 500	145 800	34.0	73.8
Average	407° C (765° F)	18 500	70 250	141 750	35.2	75.0
A-3	463° C	21 400	57 300	.....	35.5	78.1
A-16	463° C	15 300	56 000	123 700	37.0	79.2
Average	463° C (865° F)	18 350	56 650	.....	36.2	78.6
A-21	550° C	9 500	41 700	133 200	38.0	93.0
A-22	550° C	6 000	38 150	100 300	43.0	92.5
Average	550° C (1022° F)	7 750	39 950	116 750	40.5	92.7

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).

[b] Room temperature.

TABLE 5.—Tensile Properties at Elevated Temperatures of 3½ Per Cent Nickel Steel Containing 0.37 Per Cent Carbon

[Chemical composition (per cent): C, 0.37; Mn, 0.67; P, 0.021; S, 0.010; Si, 0.20; Ni, 3.43]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
B–16	(b)	47 000	105 150	172 500	30.5	50.6
B–17		56 000	104 900	164 000	27.5	46.7
B–2		.....	103 600	152 000	27.5	39.9
B–4		52 500	103 400	170 800	28.0	49.7
Average	21° C (70° F)	51 850	104 250	164 800	28.4	46.7
B–21	92° C	53 000	97 600	169 200	28.5	54.1
B–22	92° C	58 000	97 800	170 300	29.0	52.3
B–1	92° C	.....	99 600	169 500	26.0	51.3
B–3	92° C	.....	99 300	172 300	28.0	52.4
Average	92° C (198° F)	55 500	98 600	170 300	27.9	52.5
B–6	155° C	52 500	97 100	170 800	22.0	43.2
B–12	155° C	56 000	96 200	159 700	24.5	47.3
B–19	155° C	55 000	98 300	169 300	25.0	49.4
B–5	155° C	.....	95 000	161 300	23.5	48.5
Average	155° C (311° F)	54 500	96 650	165 300	23.8	47.1
B–18	241° C	42 500	104 600	181 200	25.0	51.5
B–7	241° C	.....	106 200	163 600	22.0	40.6
B–8	241° C	42 500	103 500	154 300	21.5	40.9
Average	241° C (466° F)	42 500	104 750	166 350	22.8	44.3
B–10	294° C	34 000	109 500	194 400	31.0	60.2
B–9	294° C	36 500	108 900	194 800	32.0	59.7
Average	294° C (561° F)	35 250	109 200	194 600	31.5	60.0
B–15	407° C	21 500	83 000	152 600	31.5	74.4
B–13	407° C	24 000	83 250	169 700	31.5	74.5
Average	407° C (765° F)	22 750	83 150	161 150	31.5	74.5
B–14	463° C	16 000	63 900	126 400	35.0	79.6
B–11	463° C	18 500	63 500	127 900	35.0	79.7
Average	463° C (865° F)	17 250	63 700	127 150	35.0	79.7
B–24	550° C	7 500	37 400	79 000	42.5	88.3
B–25	550° C	9 000	33 300	76 300	44.5	89.5
Average	550° C (1022° F)	8 250	35 350	77 650	43.5	88.9

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).

[b] Room temperature.

TABLE 6.—Tensile Properties at Elevated Temperatures of Nickel-Chromium Steel of the Type 3 Per Cent Nickel, 1 Per Cent Chromium, 0.4 Per Cent Carbon

[Chemical composition (per cent): C, 0.39; Mn, 0.59; P, 0.019; S, 0.009; Si, 0.23; Ni, 3.05; Cr, 0.93]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
C–14	[b]	58 500	175 000	213 700	10.0	22.9
C–15	[b]	58 500	171 800	207 000	11.0	25.2
Average	21° C (70° F)	58 500	173 400	210 350	10.5	24.0
C–2	92° C	84 700	175 000	.....	11.0	20.3
C–3	92° C	74 000	170 000	.....	11.0	23.1
Average	92° C (198° F)	79 350	172 500	.....	11.0	21.7
C–6	155° C	75 000	175 200	.....	12.5	23.2
C–7	155° C	72 500	166 000	.....	12.5	26.2
Average	155° C (311° F)	73 750	170 600	.....	12.5	24.7
C–4	241° C	63 500	181 300	.....	18.0	39.6
C–5	241° C	62 500	178 000	.....	.....	.....
Average	241° C (466° F)	63 000	179 650	.....	.....	.....
C–8	294° C	75 000	174 000	.....	23.5	62.4
C–9	294° C	80 000	171 000	.....	23.5	63.8
Average	294° C (561° F)	77 500	172 500	.....	23.5	63.1
C–10	407° C	43 000	127 600	181 200	20.0	66.5
C–11	407° C	49 000	132 200	209 000	20.0	65.4
Average	407° C (765° F)	46 000	129 900	195 100	20.0	66.0
C–12	463° C	22 000	105 000	137 700	19.0	59.9
C–13	463° C	21 500	102 500	150 300	19.0	62.0
Average	463° C (865° F)	21 750	103 750	144 000	19.0	61.0
C–16	550° C	12 000	72 100	90 000	19.0	59.0
C–17	550° C	15 000	69 500	95 750	22.5	67.3
Average	550° C (1022° F)	13 500	70 800	92 850	20.8	63.2

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).
[b] Room temperature.

TABLE 7.—Tensile Properties at Elevated Temperatures of Chromium-Vanadium Steel of the Type 1 Per Cent Chromium, 0.2 Per Cent Vanadium, 0.37 Per Cent Carbon

[Chemical composition (per cent): C, 0.37; Mn, 0.74; P, 0.020; S, 0.023; Si, 0.21; Cr, 1.04; V, 0.17]

Number	Temperature of test	Proportional limit	Tensile strength	Breaking strength[a]	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Lbs./in.²	Per cent	Per cent
D1	[b]	88 000	141 600	236 000	20.0	55.5
D-16	[b]	88 000	147 000	224 500	19.0	49.4
Average	21° C (70° F)	88 000	144 300	230 250	19.5	42.5
D-3	92° C	81 000	150 800	229 400	17.5	48.4
D-4	92° C	70 000	135 100	224 300	18.0	51.7
D-15	92° C	73 000	139 500	224 100	17.5	46.2
Average	92° C (198° F)	74 650	141 800	225 950	17.7	48.8
D-7	155° C	76 000	136 200	240 000	20.0	55.7
D-8	155° C	79 000	146 500	203 000	.....	.....
Average	155° C (311° F)	77 500	141 350	221 500	.....	.....
D-5	241° C	81 000	133 600	252 300	21.0	58.6
D-6	241° C	80 000	137 200	238 700	19.0	53.3
Average	241° C (466° F)	80 500	135 400	245 500	20.0	56.0
D-9	294° C	76 000	145 500	223 400	19.0	45.8
D-10	294° C	73 000	139 000	261 300	.....	.....
Average	294° C (561° F)	74 500	142 250	242 350	.....	.....
D-11	407° C	50 000	108 000	182 300	25.0	67.7
D-12	407° C	51 500	115 200	213 000	25.0	71.2
Average	407° C (765° F)	50 750	111 600	197 500	25.0	69.5
D-13	463° C	27 000	97 500	122 500	23.5	52.9
D-14	463° C	29 000	101 000	147 300	22.5	62.4
Average	463° C (865° F)	28 000	99 250	134 900	23.0	57.7
D-18	550° C	16 500	82 600	118 800	22.0	61.7
D-19	550° C	17 500	84 000	111 000	19.0	54.4
Average	550° C (1022° F)	17 000	83 300	114 900	20.5	58.0

[a] Breaking strength is taken as the load observed at fracture (in pounds) divided by the reduced area (in square inches).
[b] Room temperature.

Maximum strength of the carbon, 3½ per cent nickel and nickel-chromium steels, occurs between about 240 and 300° C (465 and 565° F), whereas the strength of the chromium-vanadium steel does not exceed its room temperature value within the temperature range under consideration. However, a rapid decrease in this factor is observed in all steels above 300° C (565° F).

At 550° C (1020° F) the strength of the chromium-vanadium steel is very much greater than that of the other alloys and more than twice that of the carbon steel. It has likewise decreased the least in strength from its room temperature value, as shown in Table 8. However, at all temperatures below about 475° C (885° F) the strength of the nickel-chromium steel is greater than that of the chromium-vanadium.

TABLE 8.—Comparison of Tensile Strengths of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Tensile strength at room temperature	At 550° C (1022° F)		
		Actual tensile strength	Decrease from room temperature value	Ratio of tensile strengths with carbon steel as unity
	Lbs./in.²	Lbs./in.²	Per cent	
Carbon	84 200	39 950	52.5	1.0
Nickel	104 250	35 350	66.0	.9
Nickel-chromium	173 400	70 800	59.1	1.8
Chromium-vanadium	144 300	83 300	42.4	2.1

(*b*) PROPORTIONAL LIMIT.—The proportional limits of the carbon, 3½ per cent nickel and nickel-chromium steels, increase with first rise in temperature and reach maximum values in the neighborhood of 150° C (300° F), whereas that of the chromium-vanadium steel is greatest at room temperature and, following a marked decrease, again increases perceptibly between about 150 to 250° C (300 to 480° F) before final decrease occurs. While the maximum value of the limit of proportionality of the nickel-chromium steel occurs at about 150° C (300° F) and is followed by a material decrease, a second rise in value is observed at about 300° C (570° F), so that this factor is maintained above its room temperature value until temperatures above about 370° C (700° F) are reached.

The limit of proportionality of the chromium-vanadium steel at 550° C (1020° F) has decreased proportionally more than either the carbon or nickel-chromium steels, as shown in Table 9, but its value at the high temperature indicated is greater than either of the latter and more than twice that of the carbon steel.

TABLE 9.—Comparison of Proportional Limits of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Proportional limit at room temperature	At 550° C (1022° F)		
		Actual proportional limit	Decrease from room temperature value	Ratio of proportional limits with carbon steel as unity
	Lbs./in.²	Lbs./in.²	Per cent	
Carbon	32 700	7750	76.3	1.0
Nickel	51 850	8250	84.2	1.1
Nickel-chromium	58 500	13 500	77.6	1.7
Chromium-vanadium	88 000	17 000	80.7	2.2

(c) ELONGATION AND REDUCTION OF AREA.—The effect of temperature is greater upon the values of reduction of area than elongation. In general, the inflections in the temperature elongation and temperature reduction of area curves shown in Figs. 2, 3, 4, and 5 are so varied that no attempt will be made to describe them. However, several generalizations may be made. The carbon and 3½ per cent nickel steels behave similarly, in that rise in temperature is accompanied by a general decrease in ductility, which is followed above the range 200 to 300° C (390 to 565° F) by an increase until at 550° C (1020° F) values of elongation and reduction of area are greater than those observed at room temperature.

The elongation of the chromium-vanadium steel is about the same at 550° C (1020° F) as at room temperature and does not show any very great changes throughout this temperature range, whereas elongation of the nickel-chromium steel increases to a maximum at about 295° C (565° F) (blue heat).

While the carbon and nickel steels are much more ductile at 550° C (1020° F) than either the chromium-vanadium or nickel-chromium steels, as shown in Tables 10 and 11, yet the last two alloys have high ductility, and the latter shows by far the greatest increase over its room temperature value.

TABLE 10.—Comparison of Elongations of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Elongation in 2 inches at room temperature	At 550° C (1022° F)		
		Actual elongation in 2 inches	Increase from room temperature value	Ratio of elongations with carbon steel as unity
	Per cent	Per cent	Per cent	
Carbon	30.5	40.5	32.8	1.0
Nickel	28.4	43.5	51.4	1.1
Nickel-chromium	10.5	20.8	98.0	.5
Chromium-vanadium	19.5	20.5	5.1	.5

TABLE 11. Comparison of Reductions of Area of Carbon and Alloy Steels at Room Temperature and 550° C

Steel	Reduction of area at room temperature	At 550° C (1022° F)		
		Actual reduction of area	Increase from room temperature value	Ratio of reductions of area with carbon steel as unity
	Per cent	Per cent	Per cent	
Carbon	52.8	92.7	75.5	1.0
Nickel	46.7	88.9	90.3	1.0
Nickel-chromium	24.0	63.2	163.3	.7
Chromium-vanadium	42.5	58.0	36.5	.6

(*d*) BREAKING STRENGTH.—The strength at fracture of the different steels tested, obtained by dividing the load observed at the moment of breaking by the reduced area, is shown in Fig. 6. While the data are incomplete and in some cases the variations in duplicate determinations are wide, the results are interesting when taken in conjunction with the changes previously described, for at 550° C (1020° F) the highest breaking strength is shown

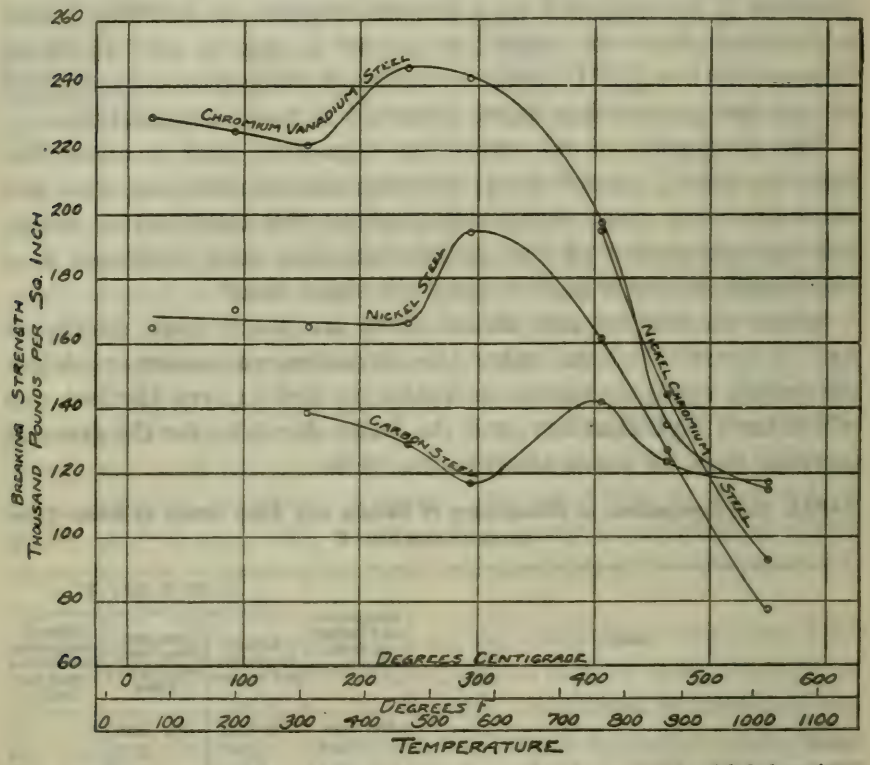

FIG. 6.—*Breaking strength at elevated temperatures of carbon, nickel, nickel-chromium, and chromium-vanadium steels. (For compositions refer to Table 3)*

by the chromium-vanadium and carbon steels and the lowest value is observed in the alloy containing 3½ per cent nickel.

2. MICROSCOPIC EXAMINATION OF FRACTURES

The fracture of steels subjected to tensile stress at room temperature is transcrystalline, while at high temperatures it takes place at the grain boundaries. The change from transcrystalline to intercrystalline fractures will occur beginning at temperatures somewhat above that of equal cohesion of the amorphous and crystalline phases, but the temperatures at which these fractures

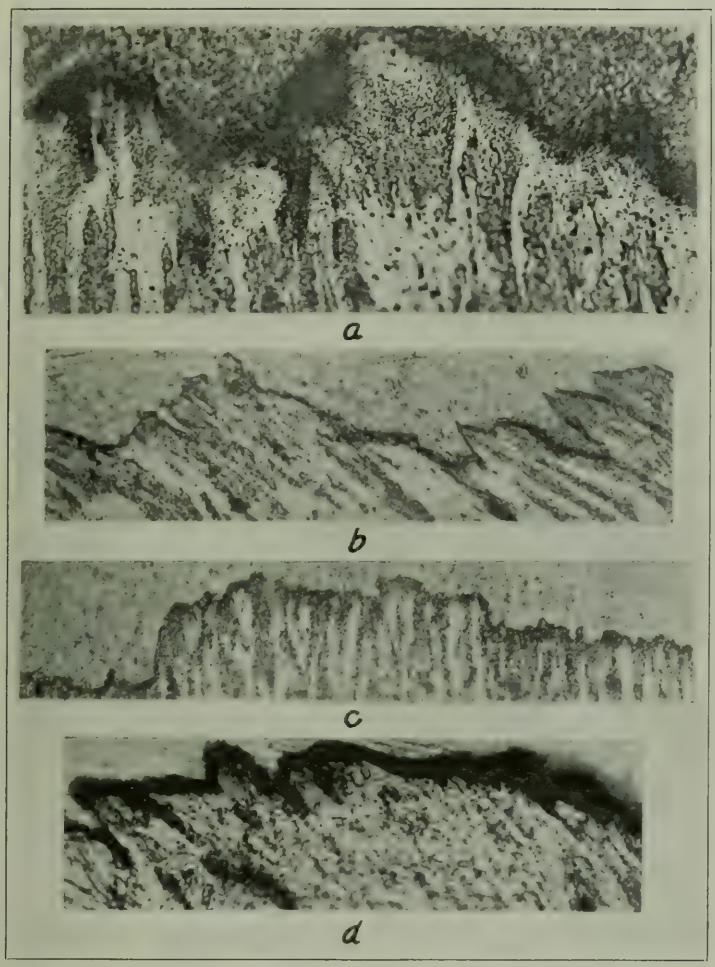

FIG. 7.—*Microphotographs of fractures of carbon and 3 1/2 per cent nickel steels broken in tension at high temperatures*

(*a*) Specimen A 16. Broken at 463° C. ×500
(*b*) Specimen A 22. Broken at 550° C. ×500
(*c*) Specimen B 11. Broken at 463° C. ×500
(*d*) Specimen B 24. Broken at 550° C. ×1000
All specimens etched with 5 per cent picric acid in alcohol

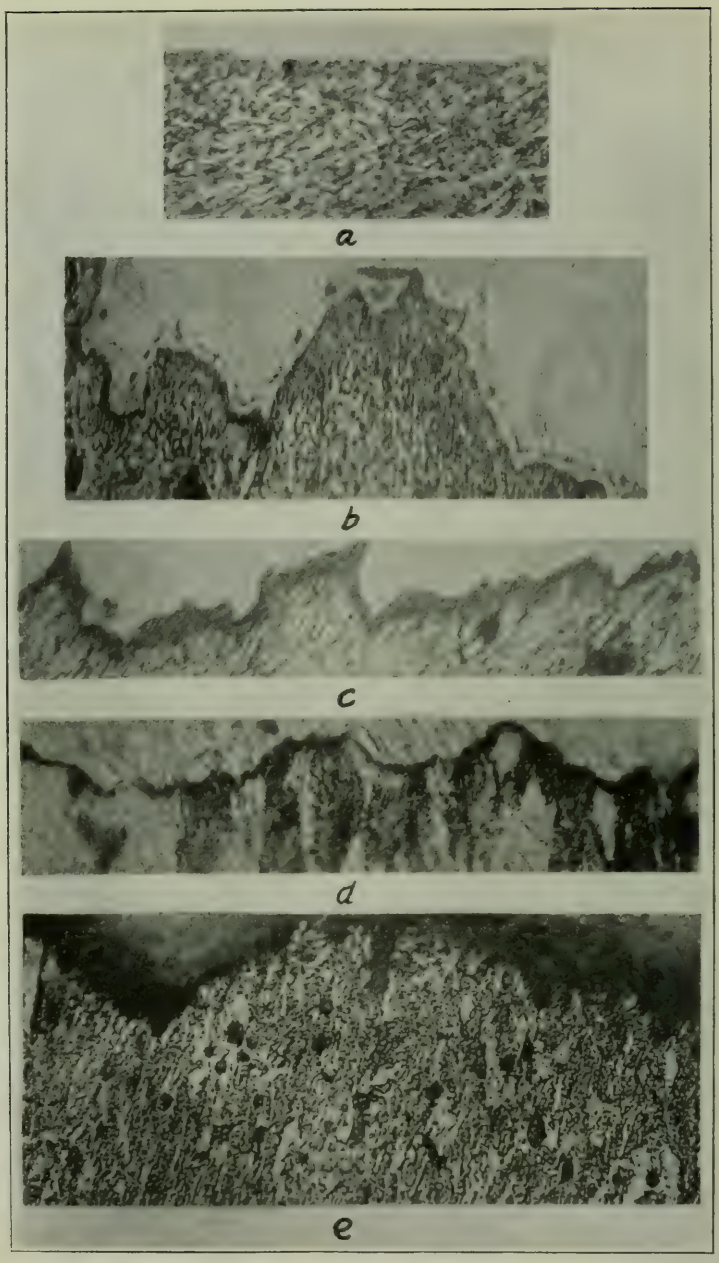

FIG. 8.—*Microphotographs of fractures of nickel-chromium and chromium-vanadium steels broken in tension at high temperatures*

(*a*) Specimen C 8. Broken at 294° C. ×1000
(*b*) Specimen C 15. Broken at 463° C. ×500
(*c*) Specimen C 16. Broken at 550° C. ×500
(*d*) Specimen D 13. Broken at 463° C. ×1000
(*e*) Specimen D 18. Broken at 550° C. ×500

a, *d*, and *e* etched with 5 per cent picric acid in alcohol; *b* and *c* with 2 per cent nitric acid in alcohol

first appear in a given alloy depend upon the rate of loading.[9] The faster the load is applied the higher is the temperature required to produce intercrystalline breaks.

Jeffries states that in most metals the equicohesive temperature occurs at about 0.35 to 0.45 of the melting point on the absolute temperature scale, so that for steels the change from fractures across the grains to those along the crystal boundaries should on slow loading first appear in the neighborhood of 550° C (1020° F). This temperature is approximately the highest at which tensile tests were made, and, as these were likewise considered of particular interest from the standpoint of operation in the Haber process, specimens of the several steels tested were examined under the microscope to determine the character of the fractures.

Typical microphotographs are reproduced in Figs. 7 and 8, and while no general statements can be made with certainty they show the tendency of the fracture in the carbon and 3½ per cent nickel steels to follow the grain boundaries when broken at about 550° C (1020° F).

The outstanding feature of the nickel-chromium steel is the fineness of the structure, making it difficult to determine the character of the break, while in the case of the chromium-vanadium steel the fractures appear more nearly intracrystalline (8*e*) even at the highest temperatures under investigation.

V. SUMMARY

The following points appear to deserve emphasis in connection with the tests previously described:

1. Of the four steels tested in normalized condition it appears that the two alloys containing chromium show greater resistance to weakening by increase in temperature to about 550° C (1020° F) than either the plain carbon or 3½ per cent nickel steels, and at this highest temperature the chromium-vanadium steel is to be preferred from the standpoint of high tensile strength and limit of proportionality.

2. The carbon and 3½ per cent nickel steels behave alike with rise in temperature, and at about 550° C (1020° F) the addition of the nickel appears to have a very small effect on the tensile properties of the carbon steel.

[9] Zay Jeffries, "Effect of temperature, deformation, and grain size on the mechanical properties of metals," Trans. A. I. M. E., **60**, p. 474; 1919.

3. At 550° C (1020° F) the strength and limit of proportionality of the chromium-vanadium steel are more than twice that of the carbon steel, while the ductility of the former, as measured by elongation and reduction of area, is about half that of the latter, though still quite high. However, at all temperatures below about 475° C (885° F) the strength of the nickel-chromium steel is greater than that of the chromium-vanadium and both show higher strength values throughout the range 20 to 550° C (70 to 1020° F) than the carbon or 3½ per cent nickel steels.

4. While no general statements regarding types of fractures can be made with certainty, the tendency of carbon and 3½ per cent nickel steels at about 550° C (1020° F) is to follow the grain boundaries, while at the same temperature the fractures of the chromium-vanadium steel appear largely transcrystalline.

ACKNOWLEDGMENT

In conclusion acknowledgment is made to C. E. Lermond, mechanical draftsman, Ordnance Department, and T. E. Hamill, laboratory apprentice, Bureau of Standards, for carrying out the greater part of the routine tensile tests reported in this paper.

WASHINGTON, August 1, 1921.

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No. 206

EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF 1 PER CENT CARBON STEEL

BY

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Bureau of Standards

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EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF 1 PER CENT CARBON STEEL

By H. J. French and W. George Johnson

ABSTRACT

The effects of varying time-temperature relations in heat treatment on tensile and impact properties, hardness, and structure of 1 per cent carbon steel have been studied, including (*a*) effect of temperature variations in hardening, (*b*) time at hardening temperatures both above A_{cm} and between the Ac_1 and A_{cm} transformations, (*c*) effects of tempering steel hardened in different ways and effects of "soaking" just under the lower critical range, (*d*) comparison of oil and water hardening for production of definite strengths.

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I. INTRODUCTION

During 1920 there was brought to the attention of one of the authors the lack of adequate information in the literature regarding the most suitable heat treatments for production of the best combinations of strength and ductility for 1 per cent carbon

steel. While considerable data are available relating to tensile properties of high-carbon alloys, it was not possible to make satisfactory comparisons between the results reported by various investigators as to the effectiveness of different treatments for the purpose in view, due to differences in chemical composition, size of specimens treated, and other factors.

Because of the varied applications of slightly supersaturated carbon steels, including tools, dies, bearings, and springs, tests were made to correlate properties and structure and determine the magnitude of the effects observed with varying time-temperature relations in certain heat-treatment operations. At the same time treatments resulting in the best tensile and impact properties were sought.

II. PREVIOUS INVESTIGATIONS

Among the tests previously reported the following are considered of particular interest in the treatment of 1 per cent carbon steel or deal with variables studied by the authors.

1. ANNEALING

Sargent[1] found greatly increased strength with increase in annealing temperatures above the critical range and a maximum when cooled from 1025° C (1877° F), which was decreased about 38 per cent when the temperature was raised to 1150° C (2102° F). Maximum ductility was obtained in slow cooling from the upper end of the critical range, while temperatures even moderately above this reduced the elongation and reduction of area to very low values. The accompanying microstructural changes were marked, and it was found that after annealing at 915° C (1679° F) the cementite surrounding grains of pearlite had all left the boundaries and "gone toward binding groups of pearlite crystals into larger compound crystals."

Campbell[2] also studied the annealing of 1 per cent carbon steel and found that maximum strength was produced after slow cooling from 905° C (1661° F), while the highest ductility and lowest strength was obtained when using 760° C (1400° F), which is slightly above or at the end of the Ac_1 transformation. In general, the inflections in curves for strength and elastic limit

[1] George W. Sargent, "A study of the effect of heat treatment on crucible steel containing 1 per cent carbon," Trans. A. I. M. E., p. 303; 1901.

[2] William Campbell, "On the heat treatment of some high carbon steels," Proc. Amer. Soc. Test. Mats., p. 211; 1906.

were accompanied by the reverse inflections in curves for elongation and reduction of area, showing that an increase in one set was obtained at the expense of the other.

Both Sargent's and Campbell's results are shown graphically in Fig. 1, while in Table 1 are given results of tests included in the Sixth Report to the Alloys Research Committee[3] for steel con-

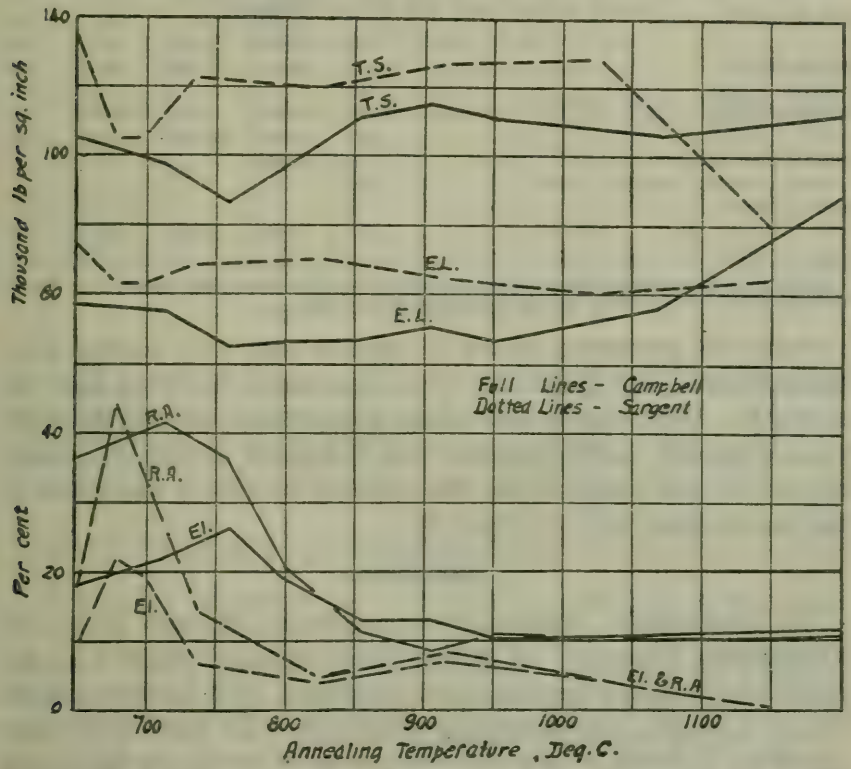

FIG. 1.—*Effect of different annealing temperatures on the tensile properties of 1 per cent carbon steel*

After Campbell and Sargent, as follows: W. Campbell, On the heat treatment of some high-carbon steels, Proc. A. S. T. M., p. 211; 1906. G. W. Sargent, A study of the effect of heat treatment on crucible steel containing one per cent carbon. Trans. A. I. M. E., p. 303; 1901.

taining 0.95 per cent carbon. Maximum strength was obtained in slow cooling from 900° C (1652° F), and the ductility gradually decreased with rise in temperature from 720° C (1328° F) to 1100° C (2012° F). Soaking decreased the strength and in general resulted in increase in elongation but decrease in reduction of area.

[3] Sir W. Roberts-Austen and W. Gowland, "Sixth Report to the Alloys Research Committee: On the heat treatment of steel," Proc. Inst. Mech. Eng., 1, p. 7; 1904.

TABLE 1.—Effect of Time and Temperature in Annealing on the Mechanical Properties of 0.95 Per Cent Carbon Steel [a]

Annealing temperature	Time at temperature	Breaking strength	Elastic limit	Elongation in 2 inches	Reduction area
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent
620° C (1148° F)	½	118 400	76 600	15.0	27.0
	12	101 800	51 800	18.5	27.1
720° C (1328° F)	½	88 000	.....	22.0	45.0
	12	75 500	31 600	23.5	35.4
800° C (1472° F)	½	89 500	50 400	18.0	28.4
	12	.....	.....	.....	.....
900° C (1652° F)	½	114 500	.....	10.0	15.4
	12	107 000	80 800	11.9	11.0
1100° C (2012° F)	½	111 300	.....	7.5	9.1
	12	.....	.....	.....	.....
1200° C (2192° F)	½	.....	.....	.....	.....
	12	53 900	45 000	20.0	37.5

[a] From Sixth Report to the Alloys Research Committee, Proc. Inst. Mech. Eng., 1904, 1, p. 7. Pounds per square inch = tons per square inch given in original table, ×2240.

From the preceding results it appears that slow cooling from temperatures just above Ac_1 gives maximum ductility and low strength. With rise in annealing temperature the ductility decreases rapidly, and elongation and reduction of area in general remain at low values, while the strength reaches a maximum in the range about 900° C (1652° F).

2. HARDENING

(*a*) Quenching Temperature.—Brinell[4] showed that the "Hardening Capacity" of carbon steels increased up to 0.45 per cent carbon when it became nearly constant, with further increase to 0.90 per cent, and thereafter decreased. The steel under consideration is therefore just above the range of maximum hardening capacity, and, as is well known, is quite sensitive to thermal treatment, having slightly more carbon than required for saturation. After quenching in cold water from temperatures above the thermal transformations it is hard and brittle, while when more slowly cooled, as in oil, high strength and somewhat greater ductility results. In either case the properties are changed to a marked degree by the quenching temperature, whether subsequent tempering is at low or high temperatures or entirely omitted, as indicated by results reported by Roberts-Austen and Gowland[5] for an

[4] Axel Wahlberg, "Brinell's method of determining hardness and other properties of iron and steel," Jr. I. and S. Inst., 1, p. 243; 1901.

[5] See note 3.

alloy containing 0.95 per cent carbon, which are reproduced in Table 2. Based on their tests, the authors conclude that the oil-quenching temperature producing the best combination of strength, elastic limit, and elongation is in the neighborhood of 900° C (1652° F).

TABLE 2.—Effect of Various Methods of Quenching and Tempering on the Tensile Properties of 0.95 Per Cent Carbon Steel [a]

QUENCHED IN WATER AT 20° C (68° F)

Quenched from—	Tempered at—	Breaking strength	Yield point	Elongation in 2 inches	Reduction of area
		Lbs./in.²	Lbs./in.²	Per cent	Per cent
720° C (1328° F)		125 500		12.0	24.8
900° C (1652° F)		48 400		Nil.	Nil.
1200° C (2192° F)		9 400		Nil.	Nil.
QUENCHED IN OIL AT 80° C (176° F)					
720° C (1328° F)		117 100	89 500	13.0	19.8
720° C (1328° F)	350° C (662° F)	122 500	81 700	12.0	18.6
870° C (1598° F)	350° C (662° F)	229 500	149 400	7.0	17.0
1000° C (1832° F)	350° C (662° F)	211 000	152 700	5.5	14.8
800° C (1472° F)	600° C (1112° F)	103 000	80 000	12.0	12.9
900° C (1652° F)	600° C (1112° F)	110 000	90 000	17.0	28.0

[a] From Sixth Report to the Alloys Research Committee, Proc. Inst. Mech. Eng., 1904, 1, p. 7. Pounds per square inch=tons per square inch given in original table, ×2240.

Hanemann [6] reported direct decrease in strength as the water, hardening temperature increased from 750 to 1000° C (1382 to 1832° F) for 1 per cent carbon steel not subsequently tempered whereas for an alloy containing 1.33 per cent carbon the strength increased until the quenching temperature exceeded 900° C (1652° F).

(*b*) Time at Hardening Temperatures.—All that is generally deemed necessary in the treatment of steel as to time at hardening temperature is to maintain it for the minimum period required for uniform heating throughout. The time actually required to meet this condition is known to increase markedly with size, and it is also known that with increased mass the temperature at which the steel will first harden rises. Portevin [7] has shown that the effect of time of heating prior to quenching is marked, and that a change from 2 to 60 minutes resulted in increased strength and hardness as shown below.

[6] H. Hanemann, "Über die Wärmebehandlung der Stahle," Stahl und Eisen, 31, p. 1365; 1911.

[7] A. Portevin, "Influence due temps de chauffage avant la trempe sur les résultats de cette operation," Rev. Met., 13, p. 9; 1916.

TABLE 3.—Effect of Time of Heating Prior to Hardening on the Mechanical Properties of 1.08 Per Cent Carbon Steel [a]

Time of heating at 800° C	Maximum strength	Elastic limit	Elongation in 100 mm (3.94 inches)	Reduction of area	Brinell hardness number
	Lbs./in.²	Lbs./in.²	Per cent	Per cent	
2 minutes	91 500	78 300	10.5	17.2	500
20 minutes	121 000	121 000	10.5	17.2	571–652
60 minutes	125 000	122 000	10.5	17.2	875

[a] A. Portevin, "Influence du temps de chauffage avant le trempe sur les resultats de cette operation," Rev. Met. (1916), 13, p. 9. Pounds per square inch=kilograms per square millimeter given in original tables, $\times 1.422 \times 10^3$.

3. TEMPERING

(*a*) TEMPERING TEMPERATURE.—The effects of tempering on the tensile and impact properties of hardened 1 per cent carbon steel have been studied by a number of investigators, including Rudeloff,[8] Hanemann,[9] and Roberts-Austen, and Gowland.[10] More recently J. H. Nead[11] determined the tensile and impact properties of such steel quenched in oil from the recommended annealing temperature range of the American Society for Testing Materials[12] when followed by tempering at various temperatures, but the possibilities for production of high combinations of strength and ductility by varying hardening and tempering treatments have not been fully covered. It appears from Nead's results, reproduced in Table 4, that tempering has a relatively small effect in reducing the brittleness of the oil quenched steel, and that tempering temperatures in the neighborhood of 500° C (932° F) are required for a material increase in ductility or decrease in tensile strength. The cause of this is undoubtedly in incomplete hardening, as specimens one-half inch or more in diameter will not be martensitic throughout after quenching in oil.

[8] M. Rudeloff, "Untersuchungen Über den Einfluss des Ausglühens auf die physicalischen Eigenschaften von Eisen und Stahdrähten." Stahl und Eisen, 12, p. 63; 1892.

[9] See note 6.

[10] See note 3.

[11] J. H. Nead, "The effect of carbon on the physical properties of heat-treated carbon steel," Trans. Amer. Inst. Min. Eng. 53, p. 218; 1915. Charpy results as related to carbon content of steel, Tests of Metals, etc., p. 109; 1916.

[12] Year Book,. Amer. Soc. Test. Materials., p. 201; 1914.

TABLE 4.—Effect of Tempering on the Mechanical Properties of Hardened 1 Per Cent Carbon Steel [a]

[Samples quenched in oil from 790° C (1454° F)]

Tempered at—	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area	Brinell hardness number	Impact energy absorbed (Charpy)
	Lbs./in.²	Lbs./in.²	Per cent	Per cent		Ft.-lbs./in.²
.....	192 500	127 000	10.5	34.0	387	.....
375° C (707° F)	195 000	127 500	12.5	34.0	375	42
460° C (860° F).....	201 500	111 000	12.5	40.3	402	41
560° C (1040° F)	168 500	104 500	14.5	30.7	321	54
650° C (1202° F)	134 000	86 000	20.0	40.3	277	57
As rolled.....	152 000	86 000	9.5	13.3	302	27

[a] J. H. Nead, "The effect of carbon on the physical properties of heat-treated carbon steel," Trans. A. I. M. E., 53 p. 218; 1915. Charpy results as related to carbon content of steel, Tests of Metals, etc., 1916; p. 109.

(*b*) TIME AT TEMPERING TEMPERATURE.—It is well recognized that a long time in tempering hardened steel at a given temperature is, within limits, equivalent to tempering for a short time at a higher temperature. Long-time tempering at a given temperature increases the ductility and lowers the strength and hardness, but the magnitude of these effects, especially at the lower tempering temperatures, depends upon the thoroughness of the hardening. The fact that Hayward and Raymond[13] found relatively small effects on the tensile properties of 0.45 per cent carbon steel with increased time of tempering was probably due in part to incomplete hardening, as pointed out in discussion of their results.

Matthews and Stagg[14] give detailed data relating to this subject, and their values are reproduced below. In part, they state

TABLE 5.—Effect of Time in Tempering Hardened Steel [a]

[Results are average of 4 check tests after each treatment, carried out on one-half-inch round tensile test bars.

Elastic limit	Maximum strength	Elongation	Reduction of area	Brinell hardness	Treatment
Lbs./in.²	Lbs./in.²	Per cent	Per cent		
228 750	260 137	2.5	.....	425	843° C (1550° F) oil, 437° C (800° F), 8 minutes
201 125	214 562	11.6	45.4	390	843° C (1550° F) oil, 437° C (800° F), 20 minutes
175 000	183 187	12.0	49.35	340	843° C (1550° F) oil, 437° C (800° F), 40 minutes

[a] J. A. Matthews and H. J. Stagg, "Factors in hardening tool steel," Trans. A. S. M. E., p. 845; 1914.

"* * * time at the drawing temperature has a marked effect. The act of breaking down the martensite is progressive and not sharply defined. Both time and temperature have their effects."

[13] C. R. Hayward and S. S. Raymond, "Effect of time on reheating hardened carbon steel below the critical range," Trans. A. I. M. E., p. 517; 1916.

[14] J. A. Matthews and H. J. Stagg, "Factors in hardening tool steel," Trans. Amer. Soc. Mech. Eng., p. 845; 1914.

Similarly, other investigators have shown the importance of the time effect in tempering, notably Barus and Strouhal,[15] who used thermoelectric methods; Goerens,[16] who studied variations in tensile, magnetic, and other properties of low carbon steel; Portevin,[17] who carried out hardness tests and microscopic examination; and likewise Rudeloff[18] and Hanemann.[19]

III. MATERIALS AND METHODS OF TESTING

The steel tested was part of a lot of 1 by ½ inch hot-rolled bars of varying carbon contents supplied by the Carnegie Steel Co., Pittsburgh, Pa., and of the following chemical composition:

	Per cent
Carbon	1.04
Manganese	.17
Phosphorus	.017
Sulphur	.019
Silicon	.14

After cutting to the desired lengths for tensile and impact specimens the steel was normalized by heating to 815° C (1500° F) for 30 minutes and cooling in still air, thereafter showing the following tensile properties and hardness:

Tensile strength, pounds per square inch	129 900
Proportional limit, pounds per square inch	55 000
Per cent elongation in 2 inches	14.0
Per cent reduction of area	22.3
Brinell hardness	217
Shore hardness	32

Test samples were machined to slightly larger than the required size (approximately ½-inch round in reduced section), subjected to various heat treatments, and finally ground wet to the form and dimensions shown in Fig. 2. Tensile tests were made with a 50 000-pound testing machine, and a strain gage was used in determination of the limit of proportionality, while hardness was obtained by both the Shore and Brinell methods, by means of a recording scleroscope and an American Brinell hardness testing machine (the latter under standard conditions of 3000 kg load and 10 mm ball). Impact specimens of both Izod and Charpy types were

[15] Barus and Strouhal, "On the physical characteristics of iron carburets," Bull. 14, U. S. Geol. Survey; 1885.

[16] P. Goerens, "Influence du traitement thermique sur les proprietes de l'acier ecruit," Rev. Met. Memoires, 10, p. 1337; 1913.

[17] A. Portevin, "Influence du temps de chauffage avant le trempe sur les resultats de cette operation," Rev. Met., 13, p. 9; 1916.

[18] See note 8.

[19] See note 6.

tested in American made Izod and Charpy machines. Prior to subjecting the steel to heat-treatment the thermal transformations were determined in a manner already described by Scott and Freeman.[20] The heating and cooling curves so obtained are shown in Fig. 3.

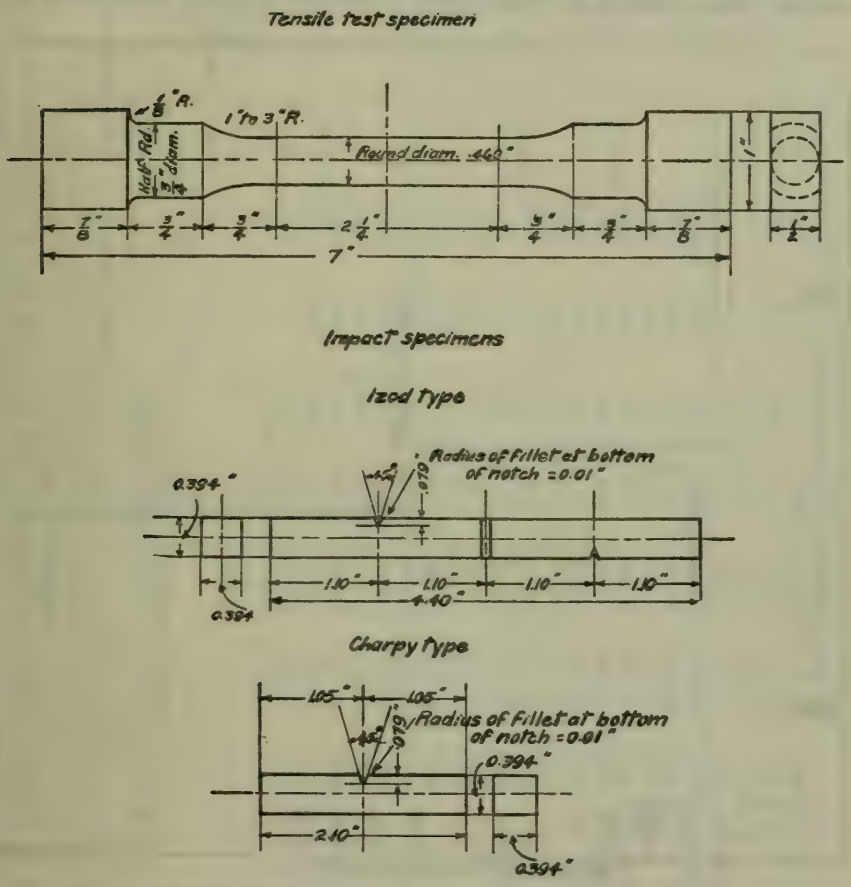

FIG. 2.—*Form and dimensions of test specimens used*

IV. EXPERIMENTAL RESULTS

1. HARDENING

(*a*) EFFECT OF QUENCHING IN DIFFERENT MEDIA.—In order to throw further light on the effect of several methods of hardening 1 per cent carbon steel when followed by high tempering, such as would possibly bring it into suitable condition for structural purposes, samples were quenched in water, oil, molten lead, and a hot

[20] H. Scott and J. R. Freemen, jr., Use of a Modified Rosenhain Furnace for Thermal Analysis, Bureau of Standards Scientific Paper No. 348, Oct. 24, 1919.

salt mixture consisting of 2 parts, by weight, of potassium nitrate and 3 parts sodium nitrate. The details of these treatments and test results are given in Table 6, and it is evident that the surface of the treated metal is an important and determining factor in the tensile properties obtained. Removal of surface irregularities resulting from scaling in treatment, including a large part or all of

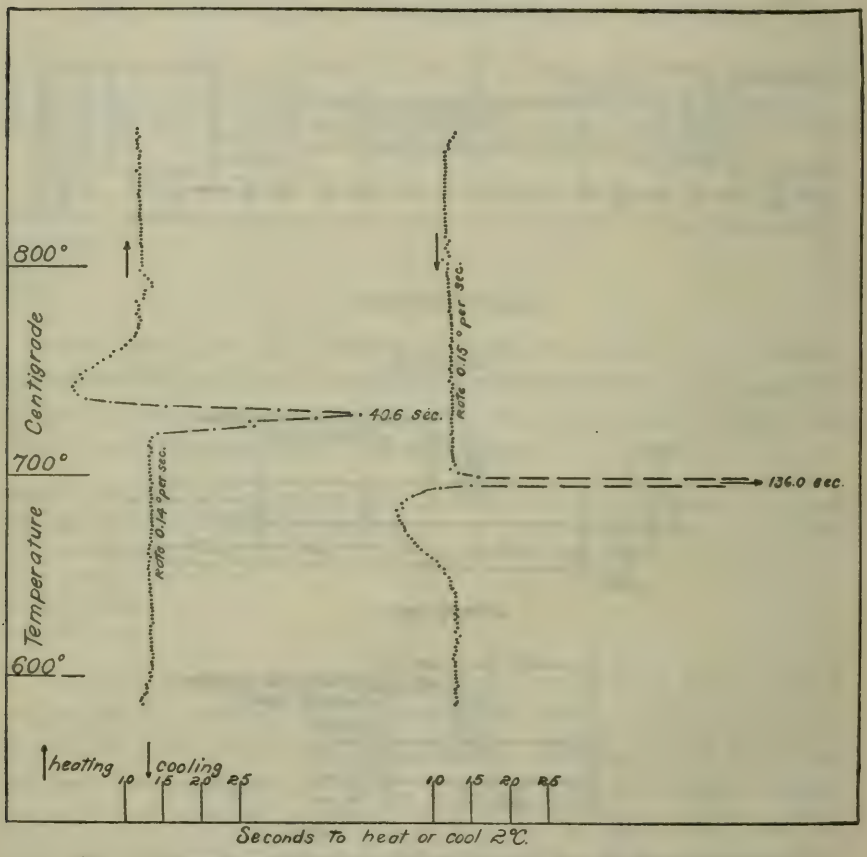

FIG. 3.—*Inverse rate heating and cooling curves of 1 per cent carbon steel*

Ac_1 (° C)			Ar_1 (° C)		
Beg.	Max.	End	Beg.	Max.	End
716	727	740	703	696	680

the decarburized surface, results in better combinations of strength and ductility, but the steel is very brittle, as shown by the low impact values, regardless of the quenching method employed. In general, the most marked effect of grinding after treatment is found in values of reduction of area, which greatly increase.

TABLE 6.—Mechanical Properties of 1 Per Cent Carbon Steel Quenched from 788° C or 843° C in Different Media and Subsequently Tempered at 538° C

Treatment	Sample No.[a]	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed, foot-pounds			
						Brinell	Shore	Charpy		Izod	
								Values	Average	Values	Average
		Lbs./in.²	Lbs./in.²	Per cent	Per cent						
788° C (1450° F), 30 minutes, water quench; tempered 15 to 20 minutes, 538° C (1000° F)	51B	165 500	143 000	11.0	27.7	340	56	2.5, 3.1, 3.2	2.9	2.2, 2.2, 2.0	2.2
	52B	156 200	132 000	12.5	34.6	340	53				
	49A	114 400	98 900	14.0	23.1	262	42				
	50A	116 200	101 400	15.0	26.1	255	43				
843° C (1550° F), 30 minutes, water quench; tempered 15 to 20 minutes, 538° C (1000° F)	49B	171 650	130 000	9.5	31.4	340	51	.....	.....	.....	.....
	50B	160 800	125 000	10.5	31.0	340	45	.....	.....	.....	.....
	51A	143 200	82 000	6.5	11.5	294	46	.....	.....	.....	.....
	52A	138 500	92 000	7.5	8.2	286	46	.....	.....	.....	.....
788° C (1450° F), 30 minutes, oil quench; tempered 15 to 20 minutes, 538° C (1000° F)	3B	188 250	110 500	.....	.....	340	48	3.0, 3.5, 2.3	2.9	2.0, 2.0, 3.0	2.3
	4B	169 000	113 000	13.0	39.3	318	48				
	13A	157 500	92 500	11.0	16.5	321	48				
	14A	156 100	90 000	10.5	16.1	321	48				
788° C (1450° F), 30 minutes, quench salt at 538° C (1000° F), holding 15 minutes before cooling in oil	43B	133 700	90 500	14.5	35.0	294	42	3.9, 3.6, 3.4	3.8	4.2, 3.4, 3.8	3.8
	44B	147 000	80 500	14.5	36.0	289	40				
	7A	143 000	81 500	8.5	22.5	278	39				
	8A	142 900	77 500	8.5	17.0	294	42				
788° C (1450° F), 30 minutes, quench lead at 538° C (1000° F), holding 15 minutes before cooling in oil	47B	151 800	84 000	15.0	37.4	255	37	3.2, 3.5, 3.0	3.2	3.1, 3.0, 3.3	3.1
	48B	148 200	81 000	14.5	36.3	278	37				
	9A	130 800	71 000	10.0	12.6	238	38				
	10A	131 200	68 500	9.5	12.4	228	31				
843° C (1550° F), 1 hour, quench lead at 538° C (1000° F), holding 30 minutes before cooling in oil	25A	136 700	70 000	12.0	23.2	248	33	.....	.....	.....	.....
	26A	139 200	72 500	10.0	15.2	278	36	.....	.....	.....	.....

[a] Samples marked B were ground wet after treatment and before testing; those marked A were tested without grinding after heat treatment.

It appears that the highest strength and ductility are obtained by cooling in oil, but a much higher elastic ratio results from water quenching. It does not necessarily follow, however, that the results reported for any quenching method are the best which

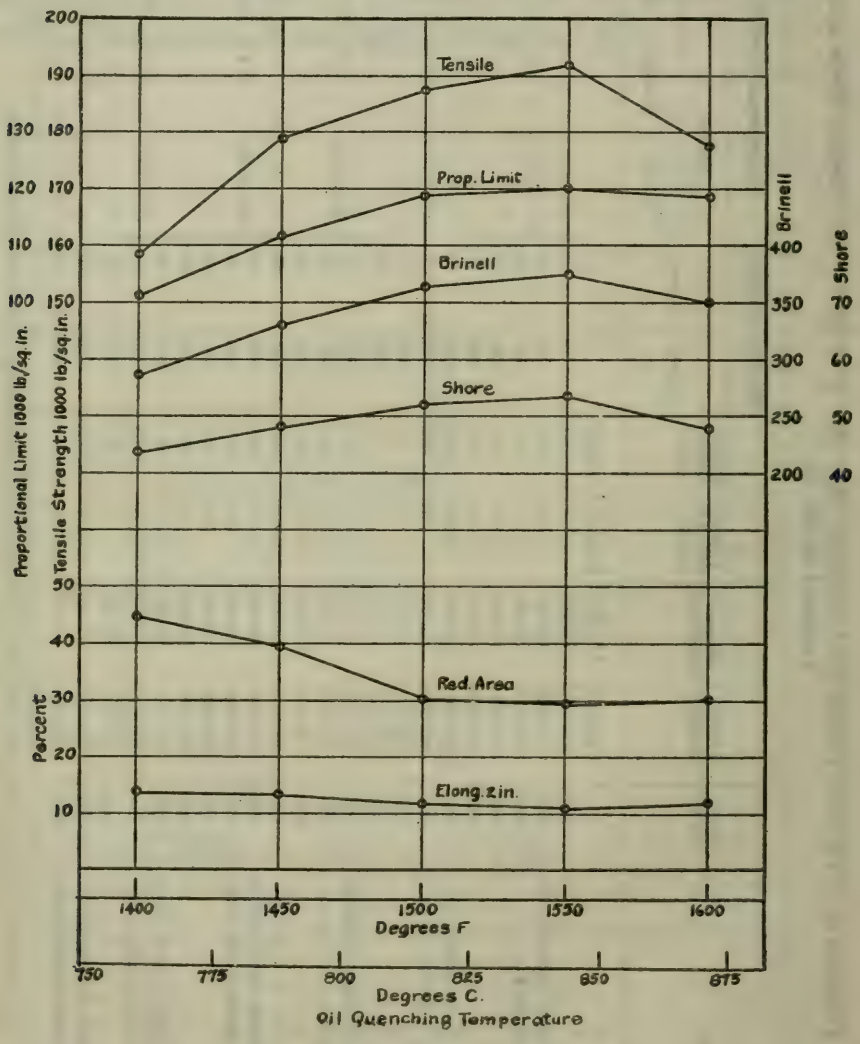

FIG. 4.—*Effect of varying oil quenching temperatures on mechanical properties of 1 per cent carbon steel subsequently tempered at 538° C*

may be produced, for it is possible that better combinations of strength and ductility may be obtained when using higher quenching temperatures than 788° C (1450° F), as is true when cooling in molten lead (Table 6).

The structures of this steel after application of these different treatments are shown in Fig. 10, and after quenching in water or oil, followed by tempering at 538° C (1000° F), the steel is sorbitic. When quenched in molten lead or salt, the steel consists of sorbitic pearlite, but the transformation appears to have progressed somewhat further to pearlite in the case of the lead quenching.

(*b*) Effect of Various Oil-Quenching Temperatures.—The effect of different oil-quenching temperatures on the properties and structures of steel subsequently tempered at 538° C (1000° F) is marked, as shown in Table 7 and Figs. 4 and 11. With rise in temperature to 843° C (1550° F) strength and limit of proportionality increase and elongation and reduction of area decrease. With further rise in quenching temperature the strength factors decrease with practically no change in ductility but in all cases the resistance to impact is low.

TABLE 7.—Effect of Varying Oil-Quenching Temperatures on the Mechanical Properties of 1 Per Cent Carbon Steel, Subsequently Tempered at 538° C

Specimen No.	Heated to temperatures noted, held 30 minutes, and quenched in oil [a]	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
1B	760° C (1400° F)	158 000	101 000	13.5	44.3	288	43	2.2; 2.5; 3.0	2.3; 2.2; 2.5
60B		.....	.....	.....	.....	.....	.....	.....	.....
Av.		.....	.....	.....	.....	.....	.....	2.6	2.3
3B	788° C (1450° F)	188 250	110 500	.....	.....	340	48	3.0; 3.5; 2.3	2.0; 2.0; 3.0
4B		169 000	113 000	13.0	39.3	318	48	3.0; 3.5; 2.3	2.0; 2.0; 3.0
Av.		178 600	111 750	13.0	39.3	329	48	2.9	2.3
5B	816° C (1500° F)	193 600	122 000	10.0	29.2	364	54	3.1; 3.3; 3.6	.....
6B		181 600	116 000	12.5	31.0	364	50	.....	.....
Av.		187 600	119 000	11.2	30.1	364	52	3.3	.....
7B	843° C (1550° F)	199 000	121 000	10.5	29.5	364	53	3.1; 3.3; 3.1	3.1; 3.2; 3.1
8B		185 000	119 000	11.5	29.5	387	54	.....	.....
Av.		192 000	120 000	11.0	29.5	376	54	3.2	3.1
9B	871° C (1600° F)	177 900	118 000	11.5	30.3	345	46	3.2; 3.9; 3.9	3.1; 2.8; 3.1
10B		177 100	119 000	12.5	29.8	356	50	.....	.....
Av.		177 500	118 500	12.0	30.0	350	48	3.7	3.0

[a] All samples subsequently tempered at 538° C (1000° F) for 20 minutes and cooled in oil.

Benedicks [21] has shown that an increase in temperature results in more rapid cooling for steel of constant mass, and that the metal passes more rapidly through the transformations. His results for an alloy containing 1 per cent carbon are reproduced in part below.

TABLE 8.—Influence of Temperature on Time of Cooling in Quenching 1 Per Cent Carbon Steel [a]

Weight of specimen in grams	Quenching temperature	Cooling time to 100° C
	° C	Seconds
12.5	950	3.07
12.3	845	4.43
12.4	750	4.11
12.3	703	5.73
12.2	695	6.20

[a] C. Benedicks, "Experimental researches on the cooling power of liquids, on quenching velocities, and on the constituents of troostite and austenite," Jr. I. and S. Inst. 2, p. 153; 1908.

It is quite evident, therefore, that a hardening of the matrix of the steel under investigation should result with rise in quenching temperatures and more carbide should be held in solution. In this case, however, there is an added factor contributing to the increased hardness and strength shown in Fig. 4 in the retention of the excess cementite when quenching from above its solution temperature range. The rate of cooling in oil when the steel is heated to 843° C (1550° F) is not sufficiently rapid to retain all this carbide in solution, but an increase to 871° C (1600° F) increases the cooling rate through the transformations enough to cause retention of the few remaining globules found after the first-mentioned treatment. These structures, as well as those obtained on using lower quenching temperatures, are shown in Fig. 11, and because of the tempering at 538° C (1000° F) the groundmass is sorbitic. There is free cementite present in good proportion until quenching temperatures above 816° C (1500° F) are used, while the condition of maximum strength obtained in the sample quenched from slightly above the A_{cm} transformation is coincident with the minimum proportion of free carbide. Undoubtedly the cementite is first wholly retained in quenching from a temperature somewhat below 871° C (1600° F), where the first disappearance has been noted, and possibly this condition

[21] C. Benedicks, "Experimental researches on the cooling power of liquids, on quenching velocities, and on the constituents of troostite and austenite," Jr. I. and S. Inst., 2, p. 153; 1908.

would be coincident with higher strength than shown in Fig. 4. However, it is acknowledged that each increase in temperature is accompanied by increased grain size. This effect opposes whatever beneficial results might be obtained by total retention of the cementite and will finally induce greater brittleness and lowered tensile strength, and that this has happened in the range under consideration is shown by the sharp decrease in strength between samples quenched from 843 and 871° C (1550 and 1600° F).

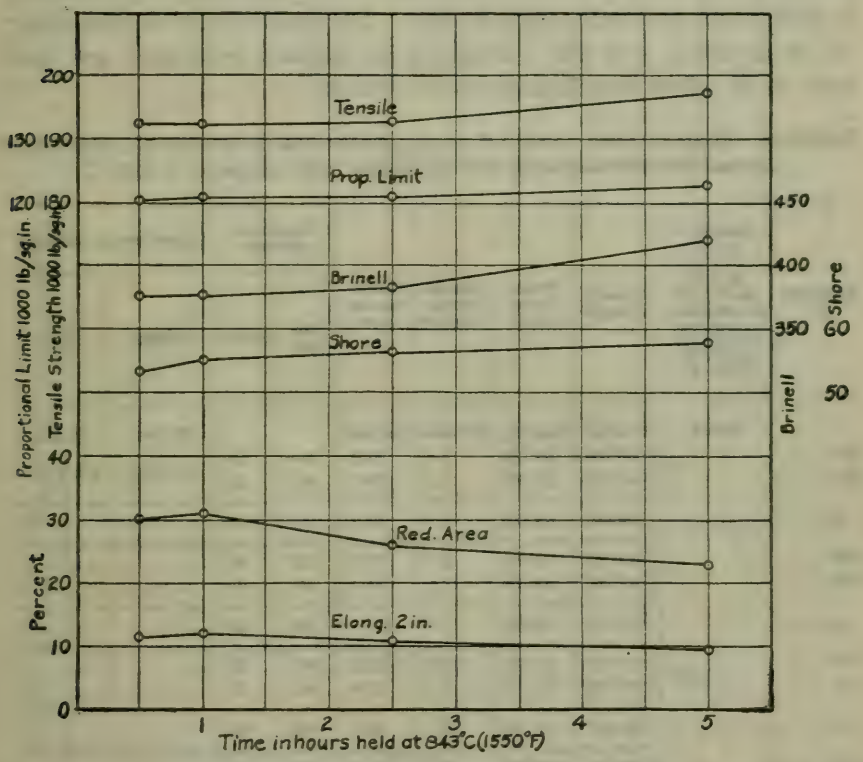

FIG. 5.—*Effect of time at 843° C on the mechanical properties of 1 per cent carbon steel subsequently oil quenched and tempered at 538° C*

(*c*) TIME OF HEATING PRIOR TO OIL QUENCHING.—In order to further investigate the magnitude of the effects of "soaking" at various hardening temperatures, samples were held for different intervals at 760° C (1400° F) and 843° C (1550° F) prior to quenching in oil and tempering. The first temperature is just above or at the end of Ac_1, while the latter is slightly above the temperature range at which the excess carbide goes into solution.

Time at Temperature Above A_{cm}.—The time (over 30 minutes) for which the steel is held at 843° C (1550° F) when subsequently oil quenched and tempered at 538° C (1000° F) has a relatively small effect on the tensile and impact properties, as shown in Fig. 5 and Table 9. A change from 30 minutes' heating to 1 hour does not alter the strength appreciably, but results in slightly increased ductility, whereas with increase in time of "soaking" from 1 to 5 hours the hardness, tensile strength, and proportional limit gradually increase with accompanying decrease in elongation and reduction of area. The steel is very brittle after all treatments, and the variations in impact resistance are not such as to allow conclusions to be drawn.

TABLE 9.—Effect of Time at 843° C on the Mechanical Properties of 1 Per Cent Carbon Steel Subsequently Oil Quenched and Tempered at 538° C

Specimen No.	Heated to 843° C (1550° F) for time noted and oil quenched; tempered 20 minutes at 538° C (1000° F)	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
7B	½	199 000	121 000	10.5	29.5	364	53	3.1, 3.3, 3.1	3.1, 3.2, 3.1
8B	½	185 000	119 000	11.5	29.5	387	53		
Av.		192 000	120 000	11.0	29.5	376	53	3.2	3.1
27B	1	202 100	128 000	10.5	27.7	387	56	.....	.....
28B	1	181 800	113 000	12.5	34.4	364	54	.....	.....
Av.		191 950	120 500	11.5	31.0	376	55	.....	.....
65B	2½	192 350	121 000	11.0	26.3	376	55	.....	.....
29B	2½	193 400	120 500	9.5	26.6	387	57	.....	.....
Av.		192 875	120 750	10.2	26.4	382	56	.....	.....
31B	5	207 900	129 500	8.5	19.5	477	56	3.2, 3.2, 4.0	3.1, 3.1, 3.0
32B	5	187 000	116 000	10.5	27.0	364	59		
Av.		197 450	122 750	9.5	23.2	421	58	3.5	3.1

The hardening temperature chosen is only slightly above the solution temperature of the excess carbide which, according to recent determination by Ishiwara,[22] takes place at about 835° C (1535° F), and that this reaction proceeds slowly is at once evident from examination of the structures shown in Fig. 12. Solution is

[22] Torajuro Ishiwara, "On the magnetic determinations of A_0, A_1, A_2, and A_3 points in steels containing up to 4.8 per cent carbon," Science Reports of the Tohoku Imperial Univ., 9, No. 5, p. 401.

incomplete at 30 to 45 minutes, whereas in 2½ hours this change has progressed nearly to completion, coincident with a marked decrease in reduction of area in tensile test. In the sample heated

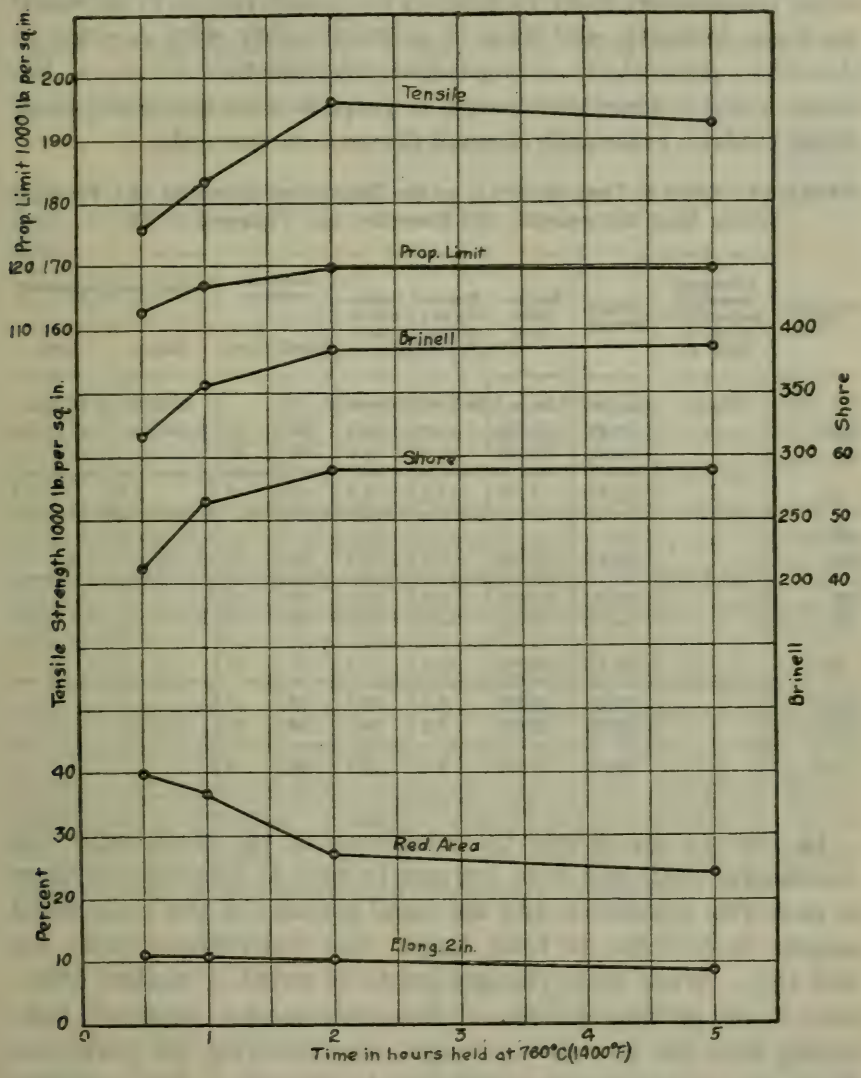

FIG. 6.—*Effect of time at 760° C on the mechanical properties of 1 per cent carbon steel subsequently oil quenched and tempered at 538° C*

for five hours the excess carbide is wholly in solution, which partly accounts for the increased hardness obtained.

Time at Temperature Between Ac_1 and A_{cm}.—When this steel is "soaked" at 760° C (1400° F), which is slightly above the end of

the Ac_1 transformation, oil quenched and subsequently tempered, as in the preceding samples, marked changes in properties result, as illustrated in Fig. 6 and Table 10. An increase in time at hardening temperature from 30 minutes to 2 hours results in increased hardness, strength, and limit of proportionality with decrease in ductility, particularly as measured by reduction of area. Between 2 and 5 hours the changes in properties are negligible, there being evident principally a small decrease in strength.

TABLE 10.—Effect of Time at 760° C on the Mechanical Properties of 1 Per Cent Carbon Steel Subsequently Oil Quenched and Tempered at 538° C

Specimen No.	Time at oil quenching temperature of 760° C (1400° F)	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
25B	½	186 800	117 500	11.0	38.1	321	45	3.1; 2.9; 3.0	2.8; 2.7; 3.0
26B	½	170 000	108 000	11.5	41.6	304	40	.....	.....
Av.	.....	175 400	112 750	11.2	39.8	313	43	3.0	2.8
37B	1	.....	.....	.....	.....	.....	.....	.....	.....
38B	1	183 250	117 000	10.5	36.8	358	53	.....	.....
39B	2	192 800	119 000	9.5	25.2	382	56	.....	.....
40B	2	198 700	120 000	10.5	29.3	387	60	.....	.....
Av.	.....	195 750	119 500	10.0	27.2	385	58	.....	.....
41B	5	192 500	118 500	8.0	20.9	376	58	.....	.....
42B	5	192 000	120 000	8.5	24.0	398	58	.....	.....
Av.	.....	192 250	119 250	8.2	22.4	387	58	.....	.....

In Fig. 13 are shown the structures of the steel under the treatments used, and with increase in time at temperature there is more free cementite, and the small globules of this constituent appear to combine to form larger ones (microphotographs 13*e* and 13*f*). While these changes are to be noted, a marked difference in the etching qualities of the groundmass is observed, indicating that the structural changes accompanying the variations in tensile properties are partly due to changes in the condition of the matrix. Specimens heated for various intervals and oil quenched without subsequent tempering were examined under the microscope and found to consist of troosto-sorbite, and it appeared that the proportion of troostite was greater the longer the "soaking."

When supplemented by Brinell hardness tests, the results of which are given in Table 11, it is evident that the effect of increasing the duration of heating for hardening results in a noticeable increase in hardness as does an increase in temperature.

TABLE 11.—Effect of Time at 760° C Prior to Oil Quenching on the Hardness of 1 Per Cent Carbon Steel

Heated at 760° C (1400° F) for time specified and oil quenched	Brinell hardness number
½ hour	340
1 hour	351
5 hours	364

2. TEMPERING

(*a*) Effect of Tempering Steel Hardened in Different Ways.—To supplement available information and correlate the tensile and impact properties of one heat of steel tempered at different temperatures after hardening in different ways, samples were tempered between 316 and 704° C (600 and 1300° F) after quenching in oil or in water from just above or at the end of Ac_1 and in oil from a temperature slightly above the A_{cm} transformation.

The results obtained in tests of steel quenched in water from 788° C (1450° F), followed by tempering between 538 and 704° C (1000 and 1300° F), are given in Fig. 7 and Table 12, and it is noted that the most rapid decrease in strength occurs when the tempering temperature is raised from about 538 to 649° C (1000 to 1200° F), while at the same time the elongation is almost doubled and reduction of area materially increased.

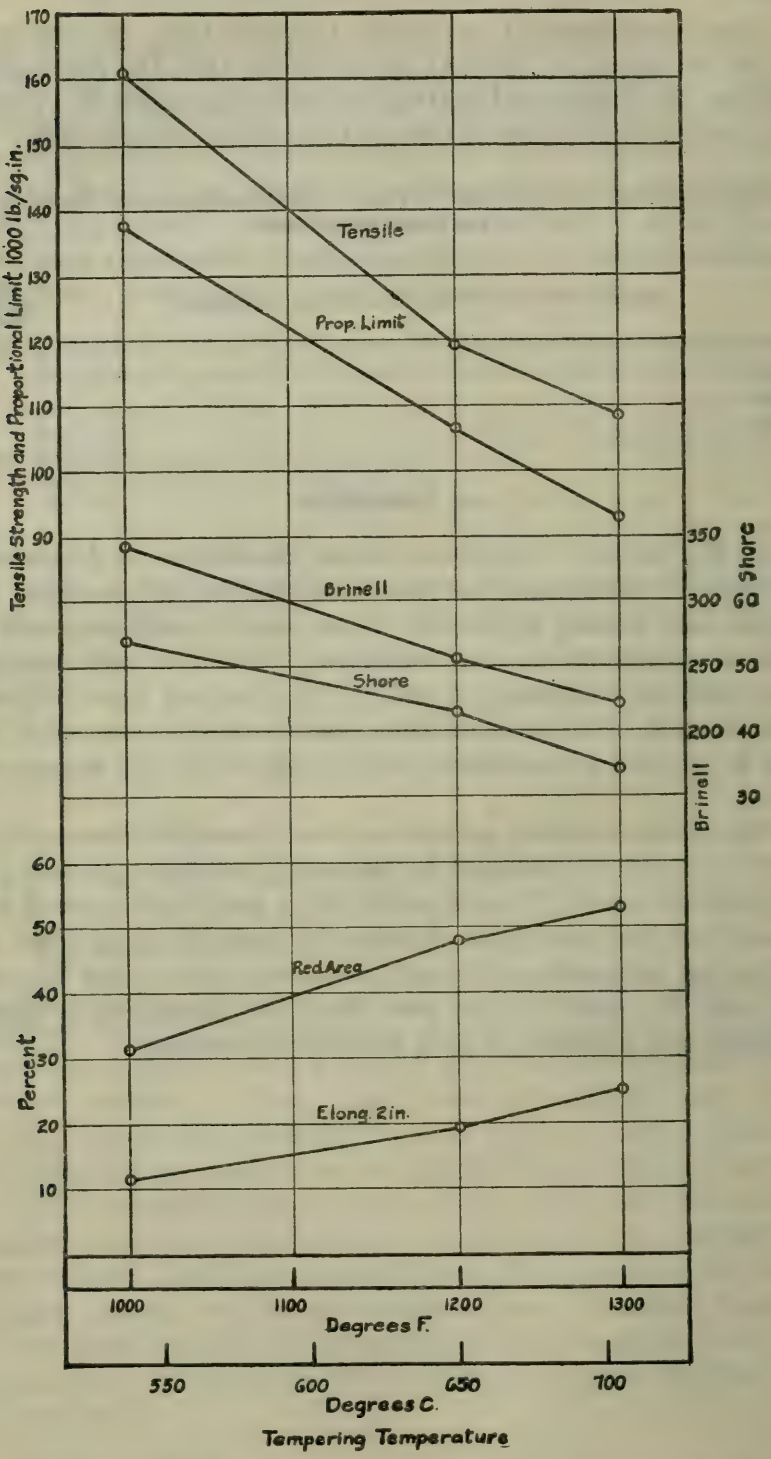

FIG. 7.—*Effect of tempering on the mechanical properties of 1 per cent carbon steel first quenched in water from 788° C*

TABLE 12.—Effect of Tempering on the Mechanical Properties of 1 Per Cent Carbon Steel First Quenched in Water from 788° C

Specimen No.	Held 20 minutes at tempering temperature indicated and air cooled	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
51B	538° C (1000° F)	165 500	143 000	11.0	27.7	340	56	2.5, 3.1, 3.2	2.2, 2.2, 2.0
52B		156 200	132 000	12.5	34.6	340	53	.....	.....
Av.	.....	160 850	137 500	11.8	31.2	340	54	2.9.....	2.1
53B	649° C (1200° F)	.....	106 509	17.0	47.4	255	43	.....	.....
54B		118 800	106 000	22.0	48.6	255	43	3.2, 2.6.....	2.3, 2.0, 2.1
Av.	.....	.....	106 250	19.5	48.0	255	43	2.9.....	2.1
55B	704° C (1300° F)	108 400	91 000	.....	.....	223	34	5.7,10.7, 8.5	11.0, 5.5, 7.7
56B		108 700	95 000	25.0	52.9	220	34	3.0, 2.9, 2.8	2.0, 2.4, 2.3
Av.	.....	108 650	93 000	.....	.....	222	34	5.6.....	5.2
67B	760° C (1400° F)	124 400	68 000	16.5	37.0	255	34	3.2, 2.3, 2.7	2.6, 2.4, 2.2
68B		115 800	67 500	18.5	44.6	269	39	.....	.....
Av.	.....	120 100	67 750	17.5	40.8	262	36	2.7.....	2.4

The mechanical properties-tempering temperature curves shown in Fig. 8 are based on results given in Table 13 for steel quenched in oil from 788 or 843° C (1450 or 1550° F) and are of the same general type. Samples quenched at the highest temperature show the highest strength with lowest elongation and reduction of area throughout than those quenched from 788° C (1450° F), or, in other words, a higher tempering temperature is required when using the highest quenching temperature to produce a given strength.

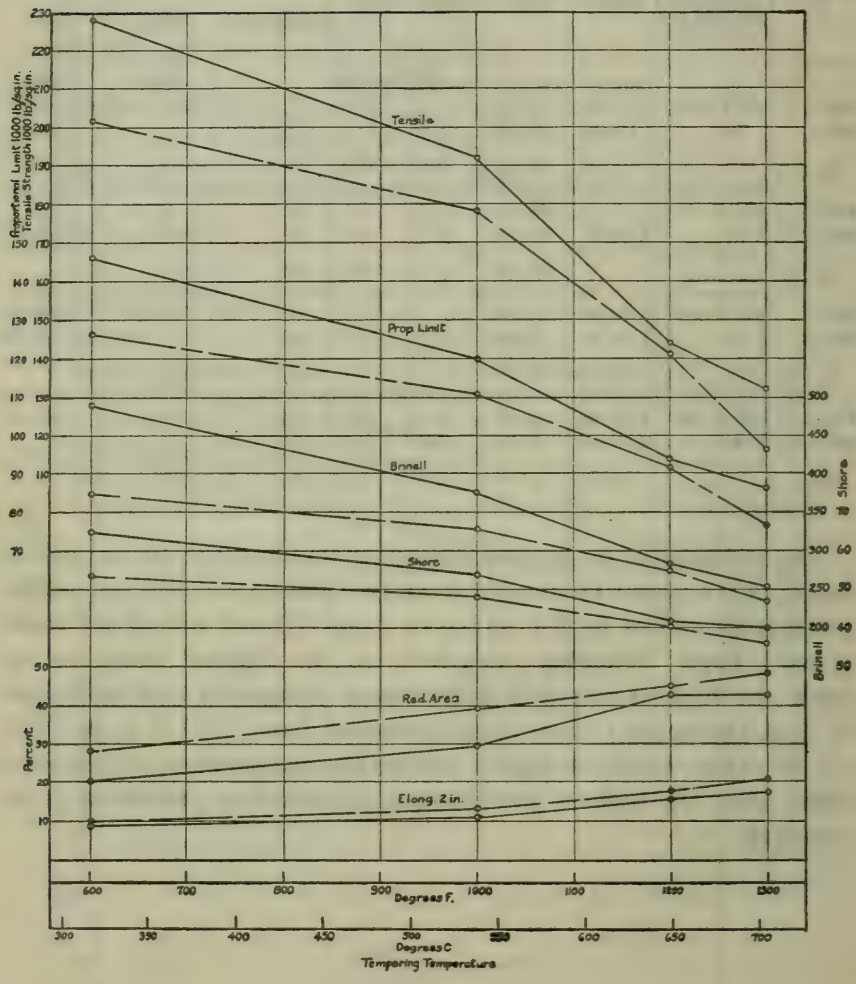

FIG. 8.—*Effect of tempering on the mechanical properties of 1 per cent carbon steel, first oil quenched from either 788 or 843° C*

Dotted lines represent samples quenched from 788° C

TABLE 13.—Effect of Tempering on the Mechanical Properties of 1 Per Cent Carbon Steel, First Oil Quenched from 788° C or 843° C

STEEL HEATED FOR 30 MINUTES AT 788° C (1450° F) AND OIL QUENCHED

Specimen No.	Held 30 minutes at tempering temperature indicated and oil quenched	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
		Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
11B	316° C (600° F)	197 000	122 000	8.0	24.8	364	52	2.2, 3.1, 3.3	2.7, 2.1, 3.3
12B		206 000	130 000	9.5	32.0	386	56	4.8, 7.5, 4.8	.....
Av.	.....	201 500	126 000	8.8	28.4	375	54	4.3	2.7
3B	538° C (1000° F)	188 250	110 500	.....	.....	340	48	3.0, 3.5, 2.3	2.0, 2.0, 3.0
4B		169 000	113 000	13.0	39.3	318	48	3.9, 3.9, 4.8	.....
Av.	.....	178 600	111 750	.....	.....	329	48	3.5	2.3
13B	649° C (1200° F)	140 700	93 000	18.0	45.3	278	41	3.0, 3.1, 3.0	2.3, 2.0, 2.4
14B		141 800	91 500	.....	.....	277	41	3.9, 4.4, 3.9	.....
Av.	.....	141 250	92 250	.....	.....	278	41	3.5	2.2
15B	704° C (1300° F)	115 800	72 500	20.0	49.8	235	36	2.8, 2.1, 2.2	3.5, 3.7, 4.0
16B		117 800	82 000	21.0	47.6	241	36	4.8	2.6, 2.1, 2.1
Av.	.....	116 800	77 250	20.5	48.7	238	36	3.0	3.0
17B	760° C (1400° F)	171 700	108 000	12.0	40.4	302	42	.....	.....
18B		171 600	110 000	11.5	42.3	286	40	.....	.....
Av.	.....	171 650	109 000	11.7	41.3	294	41	.....	.....

STEEL HEATED FOR 30 MINUTES AT 843° C (1550° F) AND OIL QUENCHED

61B	316° C (600° F)	228 000	145 000	8.0	20.3	512	66	3.1, 3.2, 3.0	4.0, 2.7, 3.8
62B		228 200	147 000	8.0	20.3	470	64	8.0, 2.2	.....
Av.	.....	228 100	146 000	8.0	20.3	491	65	3.9	3.5
7B	538° C (1000° F)	199 000	121 000	10.5	29.5	364	53	3.1, 3.3, 3.1	3.1, 3.2, 3.1
8B		185 000	119 000	11.5	29.5	387	54	.....	.....
Av.	.....	192 000	120 000	11.0	29.5	376	54	3.2	3.1
22B	649° C (1200° F)	.....	90 500	17.5	45.6	277	42	3.9, 4.8, 4.8	3.5, 3.5, 3.5
63B		144 700	98 500	15.0	41.0	290	42	.....	.....
Av.	.....	144 700	94 500	16.2	43.3	284	42	4.5	3.5
23B	704° C (1300° F)	125 200	86 000	18.8	46.7	260	40	3.3, 3.0	3.0, 2.8, 3.0
24B		140 200	.....	17.0	40.2	248	40	9.6, 6.6, 4.8	4.5, 5.5, 6.0
Av.	.....	132 700	86 000	17.9	43.4	254	40	5.5	4.1
25B	760° C (1400° F)	186 800	117 500	11.0	38.1	319	45	3.1, 2.9, 3.0	2.8, 2.7, 3.0
26B		170 000	108 000	11.5	41.6	332	40	.....	.....
Av.	.....	178 400	112 750	11.2	39.8	326	43	3.0	2.8

By interpolation of the graphs giving variations in tensile properties of the tempered steel hardened in different ways it is possible to compare the various treatments applied in order to produce a given strength, and the results obtained from this approximation are given in Table 14.

TABLE 14.—Comparison of Oil and Water Hardening of 1 Per Cent Carbon Steel for Production of Definite Strengths

[Approximate values by interpolation]

Strength chosen in pounds per square inch	Method of hardening	Tempering required	Proportional limit	Elastic ratio	Elongation in 2 inches	Reduction of area	Hardness number	
							Brinell	Shore
			Lbs./in.²	Per cent	Per cent	Per cent		
200 000.....	843° C oil....	489° C (912° F)	125 000	62.5	10.5	27.5	400	56
	788° C oil....	331° C (628° F)	125 000	62.5	10.0	29.0	370	53
160 000.....	843° C oil....	611° C (1132° F)	102 500	64.0	14.0	38.5	312	46
	788° C oil....	591° C (1096° F)	101 500	63.5	15.5	42.2	302	44
	788° C water.	540° C (1004° F)	136 500	85.3	12.0	32.0	342	54
135 000.....	843° C oil....	690° C (1274° F)	88 000	65.1	19.5	48.0	260	41
	788° C oil....	661° C (1222° F)	87 500	64.8	18.5	45.5	265	39
	788° C water.	608° C (1126° F)	118 000	87.3	17.0	42.0	290	47
120 000.....	788° C oil....	696° C (1284° F)	78 000	65.0	20.0	48.0	240	37
	788° C water.	648° C (1198° F)	107 000	89.0	19.0	48.0	260	43

For the production of given strength by heat treatment a slightly higher tempering temperature is required after oil quenching from just above the Ac_1 transformation than when the steel is water quenched from the same temperature.

Likewise a higher temperature is required when oil quenching from above the A_{cm} transformation than when similarly cooled from just above Ac_1 in order to produce the same strength. In general, this difference is less as the temperatures at which the steel is tempered increases.

Water-quenched steel subsequently tempered to show the same strength as that quenched in oil and tempered has a very much higher proportional limit than the latter and also greater hardness as measured by the Brinell and Shore methods. As the tempering temperature approaches the lower critical range these differences at first decrease and then slightly increase. While the difference between the hardness of water and oil quenched steels is well known, it is interesting to note the magnitude of this difference for the steel under consideration and the fact that it is maintained over a wide range of tempering.

In view of the slight differences in tensile properties between the steel quenched in oil from 788° C (1450° F) and that from 843° C (1550° F) the lower temperature is recommended. If the excess carbide exists in plate form, due to a previous high heating, it may readily be refined by normalizing. A preliminary quench from above A_{cm}, however, appears preferable. Water hardening is the best method for the production of strengths in the neighborhood of 120 000 lbs./in.^{2} requiring a tempering of about 649 to 710° C (1200 to 1300° F), providing always that the size and shape of the material is such as to allow the use of a drastic quenching medium.

The structures of samples subjected to the various tempering treatments are shown in Figs. 14 and 15 and are of the usual type. After short-time tempering at 316° C (600° F) the steel is troosto-sorbitic, and as the tempering temperature increases there is a gradual transition of the groundmass to its more stable form. The water-quenched steel, however, has the finest structure regardless of the tempering temperature used.

(*b*) Effect of Time in Tempering at a Temperature Slightly Below Ac_1.—The effect of "soaking" at 704° C (1300° F) when followed by quenching in oil on the properties of oil-hardened steel is shown in Fig. 9 and Table 15. A change from one-half hour to five hours has reduced the hardness considerably, the strength by about one-third, and markedly increased the ductility. As shown in Fig. 16, there is very little change in the character of the excess carbide with increased heating time, so that the change in properties is a result of a distinct softening of the matrix. Comparison of the tensile properties shown in Fig. 9 with results obtained on normalized steel at once shows the effectiveness of temperatures just under the lower transformation for softening this alloy.

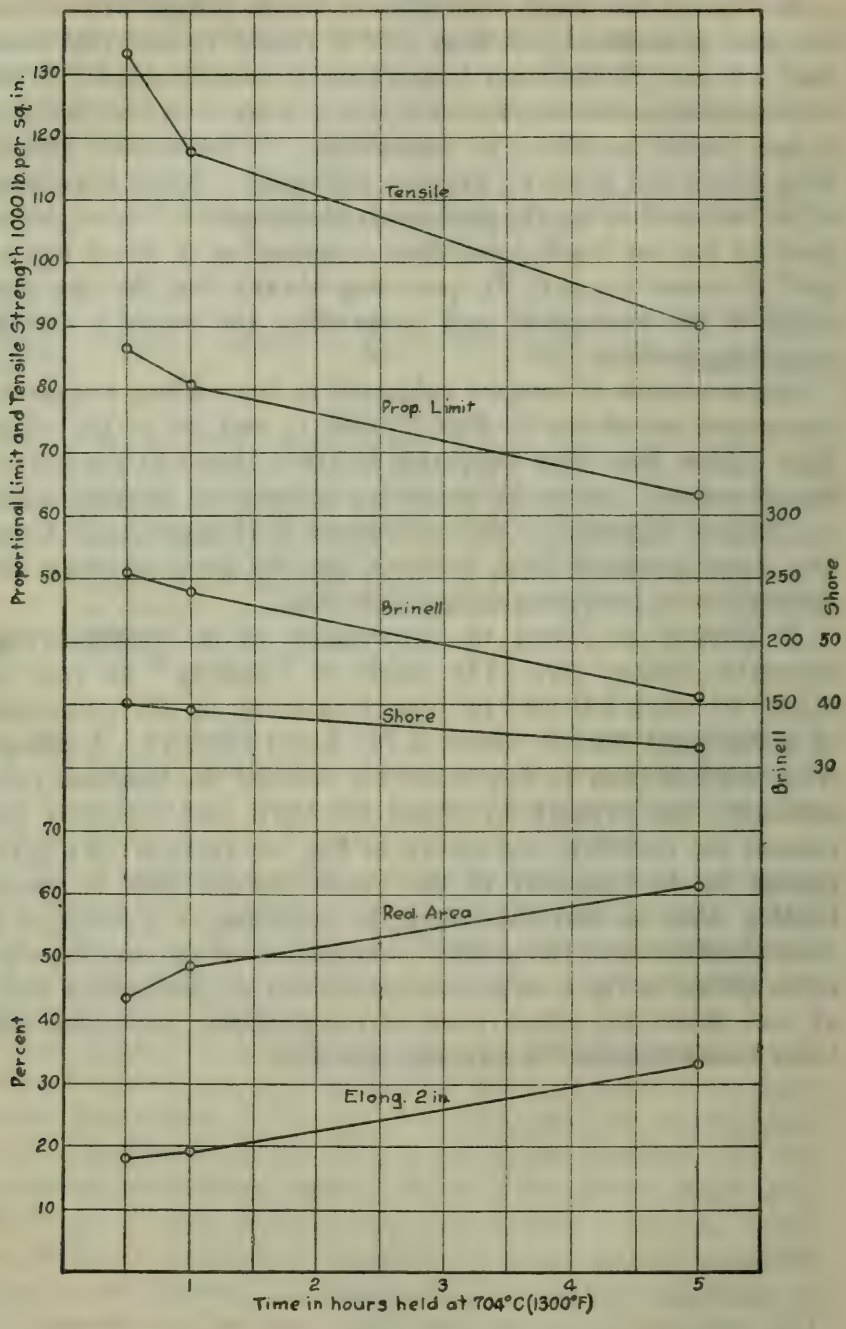

FIG. 9.—*Effect of time at a temperature slightly below* Ac_1 *on the mechanical properties of 1 per cent carbon steel previously oil quenched from 843° C*

Samples were oil quenched from the tempering temperature

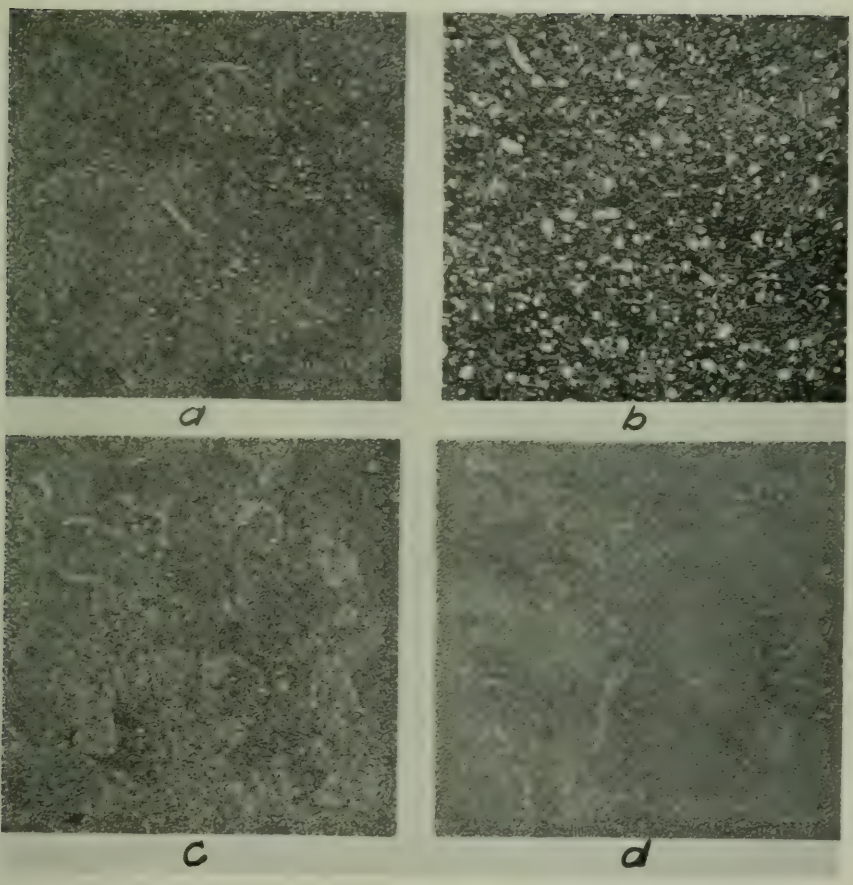

FIG. 10.—*Microstructure of 1 per cent carbon steel quenched from 788° C in different media and tempered at 538° C.* ×500

(*a*) Quenched in water
(*b*) Quenched in oil
(*c*) Quenched in molten lead at 538° C
(*d*) Quenched in molten sodium and potassium nitrates at 538° C
All samples etched with 2 per cent nitric acid in alcohol

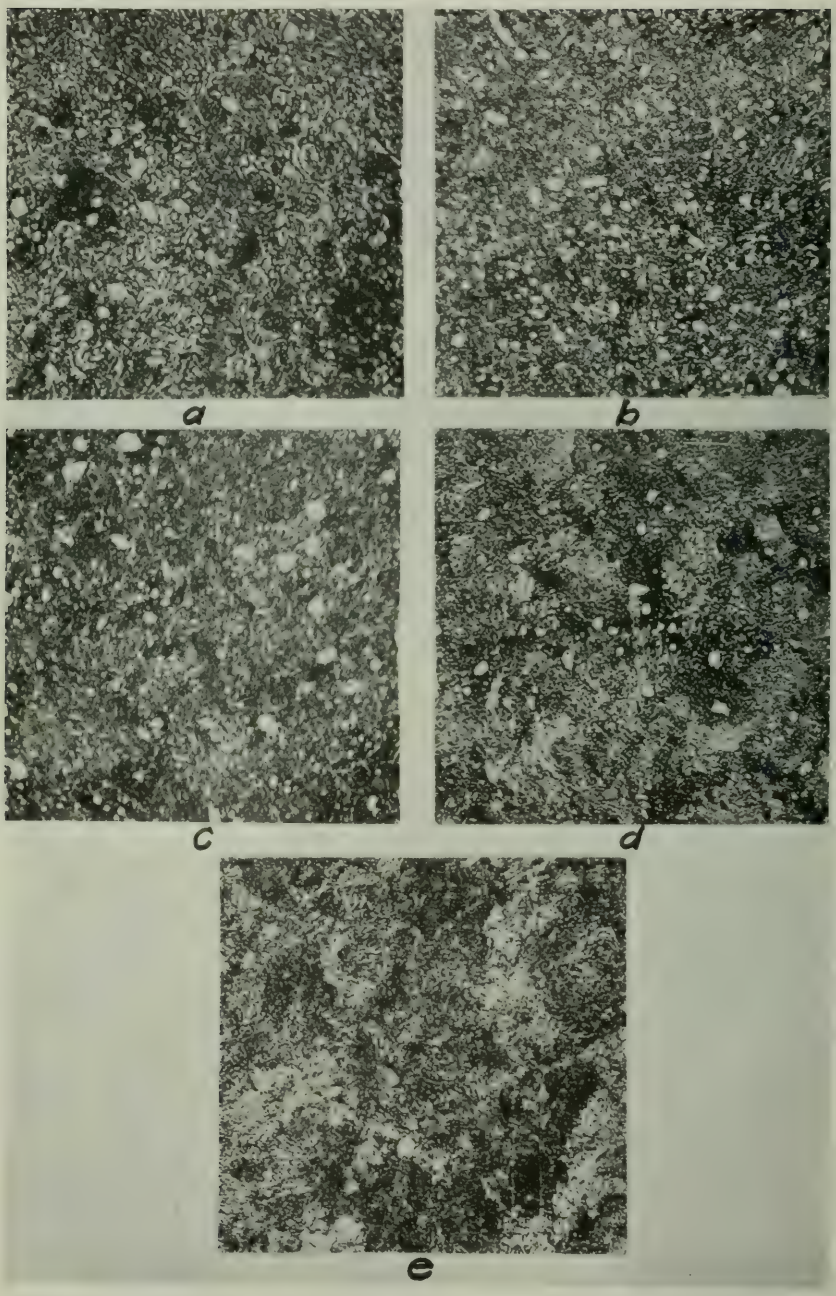

FIG. 11.—*Microstructure of 1 per cent carbon steel oil quenched from various temperatures and subsequently tempered at 538° C.* ×500

(*a*) 760° C (1400° F)
(*b*) 788° C (1450° F)
(*c*) 816° C (1500° F)
(*d*) 843° C (1550° F)
(*e*) 871° C (1600° F)

Samples etched with 2 per cent nitric acid in alcohol

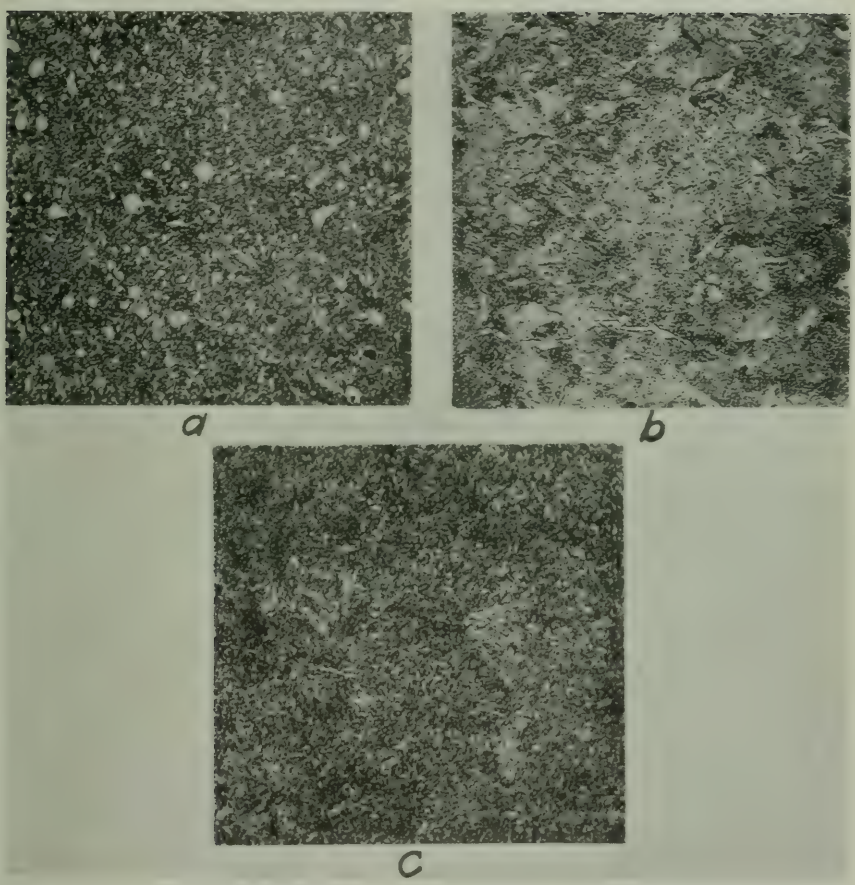

FIG. 12.—*Microstructure of 1 per cent carbon steel held at 843° C for various times and subsequently oil quenched and tempered at 538° C.* ×500

(*a*) 45 minutes (*b*) 2½ hours (*c*) 5 hours

Samples etched with 2 per cent nitric acid in alcohol

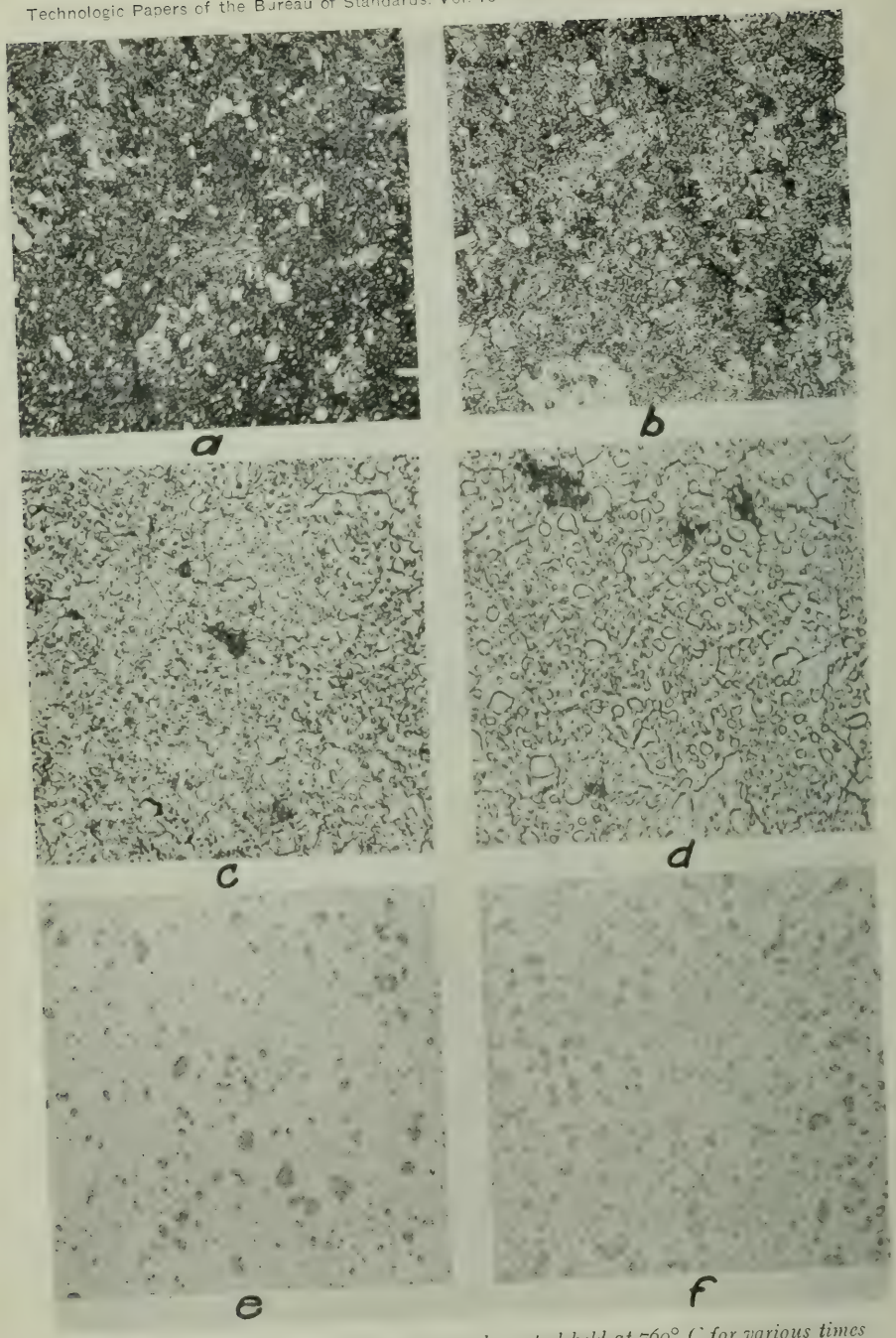

FIG. 13.—*Microstructure of 1 per cent carbon steel held at 760° C for various times and subsequently oil quenched and tempered at 538° C.* ×500

(*a*) ½ hour (*b*) 1 hour (*c*) 2 hours (*d*) 5 hours (*e*) ½ hour (*f*) 5 hours
Samples (*e*) and (*f*) etched with boiling sodium picrate. Other samples etched with 2 per cent nitric acid in alcohol

TABLE 15.—Effect of Time Slightly Below Ac_1 on the Mechanical Properties of 1 Per Cent Carbon Steel, Previously Oil Quenched from 843° C

Specimen No.	Heated at 704° C (1300° F) for time specified and then oil quenched	Tensile strength	Proportional limit	Elongation in 2 inches	Reduction of area	Hardness number		Impact energy absorbed	
						Brinell	Shore	Charpy	Izod
	Hours	Lbs./in.²	Lbs./in.²	Per cent	Per cent			Ft.-lbs.	Ft.-lbs.
23B	½	126 200	86 000	18.8	46.7	260	40	3.3, 3.0	3.0, 2.8, 3.0
24B	½	140 200	.....	17.0	40.2	248	40	.....	4.5, 5.5, 6.0
Av.		133 200	86 000	17.9	43.4	254	40	3.2	4.1
34B	1	121 500	79 000	.....	.....	241	39	.....	.....
64B	1	113 200	81 500	19.0	48.4	235	39	.....	.....
Av.		117 350	80 250	.....	.....	238	39	.....	.....
35B	5	86 100	54 500	33.0	61.3	156	32	2.8, 8.4, 2.5	2.6, 2.3, 3.9
36B	5	93 900	72 000	.....	.....	207	34	.....	.....
Av.		90 000	63 250	.....	.....	182	33	4.6	2.9

V. DISCUSSION

As far as the tensile and impact properties of heat-treated 1 per cent carbon steel are concerned certain facts deserve emphasis in connection with the tests previously described. The steel remains extremely brittle, even though good combinations of tensile strength and ductility are obtained by suitable treatment. Such low resistance to impact makes the surface condition of the metal of great importance, so that moderately sharp corners and even scratches may greatly effect the behavior of the steel in service.

It is extremely sensitive to heat treatment. Small changes in the hardening temperature produce large differences in tensile properties, though after quenching in a given medium as in oil such differences may be largely removed by varying the tempering temperature.

To retain all excess cementite in solution when quenching in oil requires a relatively high temperature. The lowest temperature at which this may be brought about is, among other factors, dependent upon the time of heating prior to hardening and is lower the longer the "soaking," but must be at or above the range of solution of this carbide. Between Ac_1 and A_{cm} the excess cementite spheroidizes and coalesces to form larger globules, which are retained in the free state in the oil-quenched steel.

At temperatures slightly below Ac_1 long-time heating when followed by cooling in oil produces no change in the condition of the cementite which may be readily observed under the microscope.

In this connection attention is directed to a recent study of the formation of spheroidal cementite by Honda and Saito.[23] The authors conclude that spheroidization of granular pearlite takes place below Ac_1 if held at temperature for a sufficiently long time, but that spheroidization of lamellar pearlite can not proceed until Ac_1 has been reached or exceeded. If the maximum temperature in heating exceeds a certain limit above this formation, the cementite appears as a lamellar pearlite on cooling, and therefore no spheroidization will take place.

The tests carried out in this investigation further indicate the importance of time at temperatures between Ac_1 and A_{cm} (Fig. 6). The sensitivity of 1 per cent carbon steel in this temperature range (within which it is ordinarily heated for hardening) to varying time-temperature relations is great, and the data obtained show why widely different results may so readily be obtained in the application of the heat-treated product.

VI. SUMMARY AND CONCLUSIONS

Based on the tests made under conditions previously described, the following conclusions are drawn:

1. The most suitable oil or water quenching temperature for steel which is subsequently to be tempered at relatively high temperatures is slightly above the end of the Ac_1 transformation.

2. With increase in oil-quenching temperature for steel subsequently tempered at 538° C (1000° F) hardness, strength, and limit of proportionality increase and maximum values are obtained after quenching from 843° C (1550° F) which is coincident with retention of all but a small portion of the excess cementite. A higher quenching temperature results in decreased strength.

3. When this steel is subsequently to be tempered to produce tensile strength in the neighborhood of 120 000 lbs./in^2 water quenching is to be preferred on account of the higher elastic ratio produced, always assuming that the size and shape of material is such as to allow drastic treatment. If higher strength is desired (which condition requires lower tempering), oil quenching from

[23] K. Honda and S. Saito, "On the formation of spheroidal cementite," Jr. I. and S. Inst., 2, p. 261; 1920.

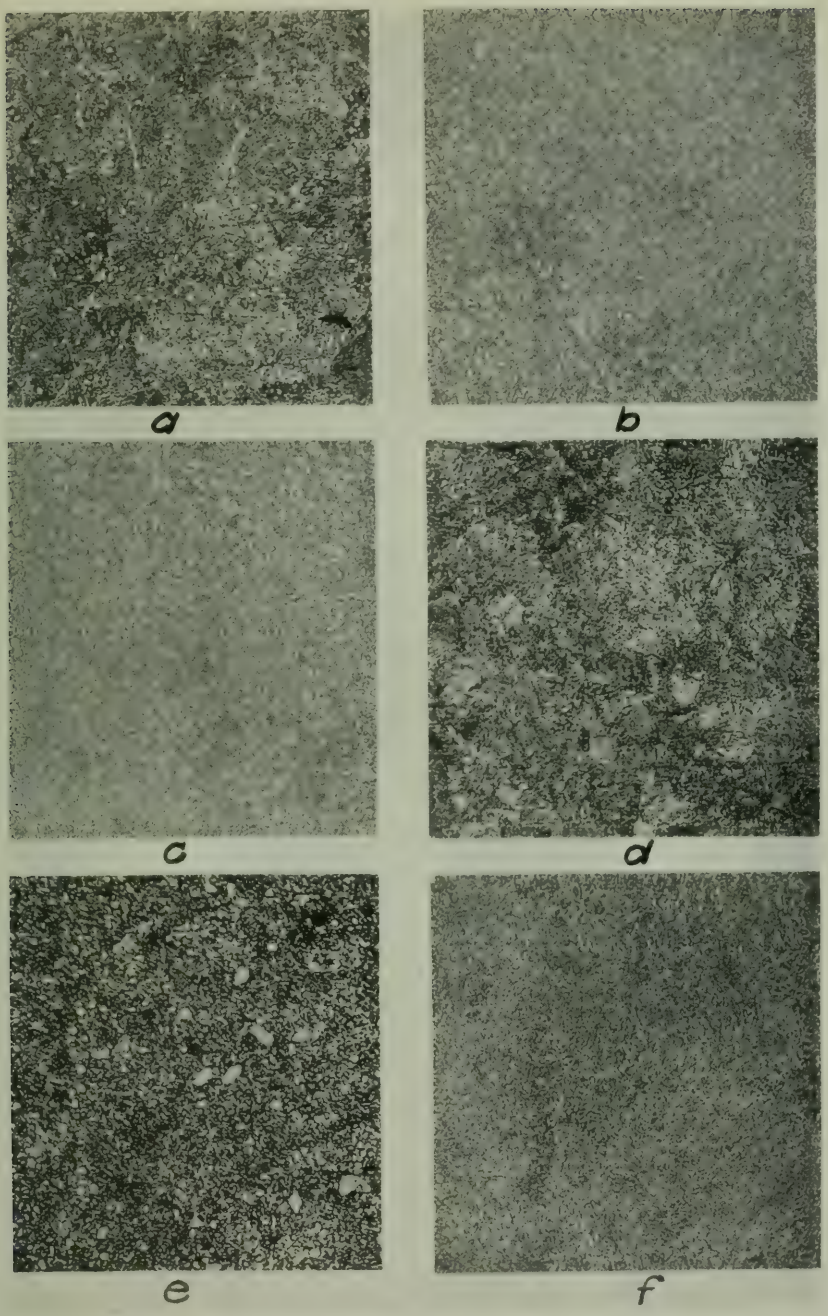

FIG. 14.—*Microstructure of 1 per cent carbon steel oil quenched from 788° C or 843° C and subsequently tempered at different temperatures.* ×500

(*a*) Quenched from 788° C and tempered at 316° C (600° F)
(*b*) Quenched from 788° C and tempered at 649° C (1200° F)
(*c*) Quenched from 788° C and tempered at 704° C (1300° F)
(*d*) Quenched from 843° C and tempered at 316° C (600° F)
(*e*) Quenched from 843° C and tempered at 649° C (1200° F)
(*f*) Quenched from 843° C and tempered at 704° C (1300° F)
All samples etched with 2 per cent nitric acid in alcohol

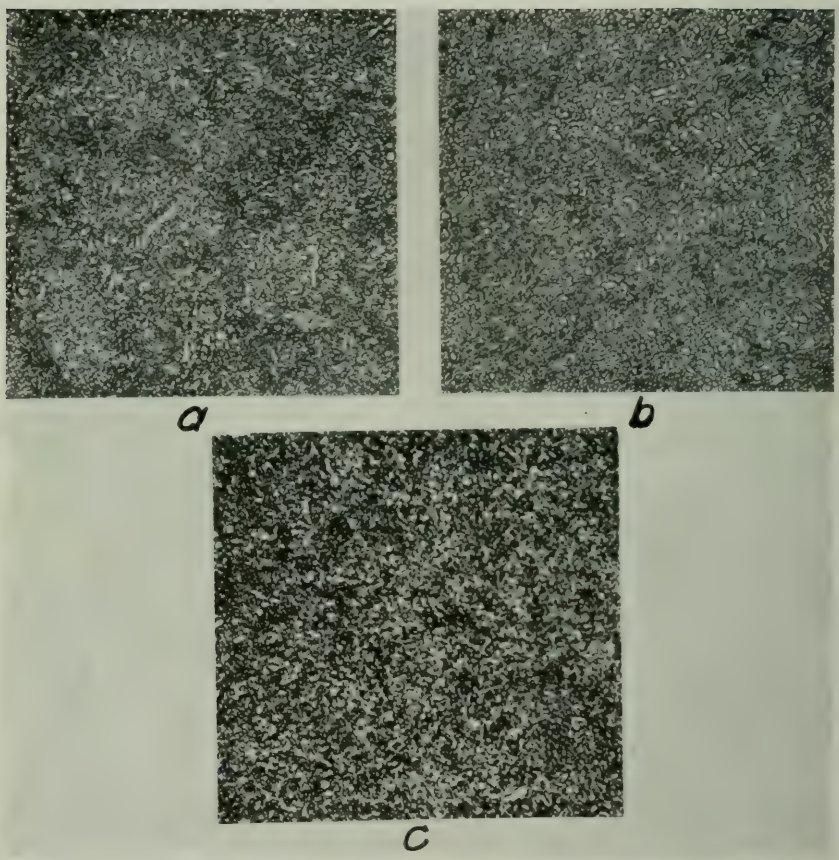

FIG. 15.—*Microstructure of 1 per cent carbon steel water quenched from 788° C and subsequently tempered at different temperatures.* ×500

(*a*) 538° C (1000° F) (*b*) 649° C (1200° F) (*c*) 704° C (1300° F)
Samples etched with 2 per cent nitric acid in alcohol

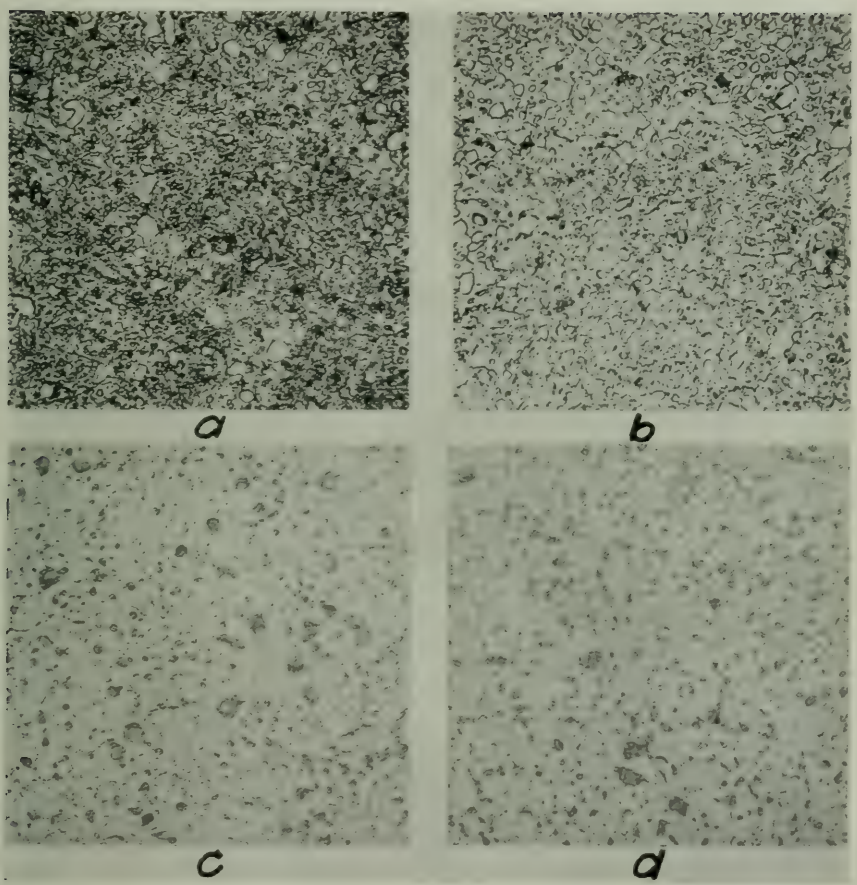

FIG. 16.—*Microstructure of 1 per cent carbon steel oil quenched from 843° C and subsequently tempered for various times at a temperature slightly below* Ac_1. ×500

(*a*) 1 hour (*b*) 5 hours (*c*) 1 hour (*d*) 5 hours
(*a*) and (*b*) etched with 2 per cent nitric acid in alcohol; (*c*) and (*d*) etched with boiling sodium picrate

just above the Ac_1 transformation will give slightly better combinations of strength and ductility but with lower elastic ratio than are obtained by water hardening.

4. A lower tempering temperature is required after water hardening than when cooling in oil from the same temperature in order to produce the same strength. This difference in temperature in general increases the higher the strength required (the lower the tempering temperatures).

5. When samples are quenched in water and others quenched in oil and all so tempered as to produce the same strength, the water-quenched steel will have the highest hardness as determined by the Brinell and Shore methods.

6. While good combinations of tensile strength and ductility may be obtained by tempering at the higher tempering temperatures, the steel is brittle and has low resistance to impact. This is shown by the much higher combinations of strength and ductility obtained in tensile tests when the steel is ground to size after heat treatment and by the low Charpy and Izod values obtained in all cases.

7. Increased time at hardening temperatures results in increased hardness, strength, and limit of proportionality, and decreased ductility, as does rise in temperature.

8. Long-time heating just under the lower critical range results in a material softening of the steel, equivalent to a decrease of 40 per cent in Brinell hardness and 20 per cent in Shore hardness when the time at temperature is increased from 30 minutes to 5 hours. Short-time heating in this temperature range results in a softer steel than that air cooled from above the transformations.

9. The changes in physical properties which have been described are in all cases coincident with well-defined structural changes.

Acknowledgment is made to T. E. Hamill, laboratory aid of the Bureau of Standards, for assistance in carrying out the various heat treatments and physical tests involved.

WASHINGTON, June 30, 1921.

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 207

MANUFACTURE AND PROPERTIES OF STEEL PLATES CONTAINING ZIRCONIUM AND OTHER ELEMENTS

BY

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Bureau of Standards

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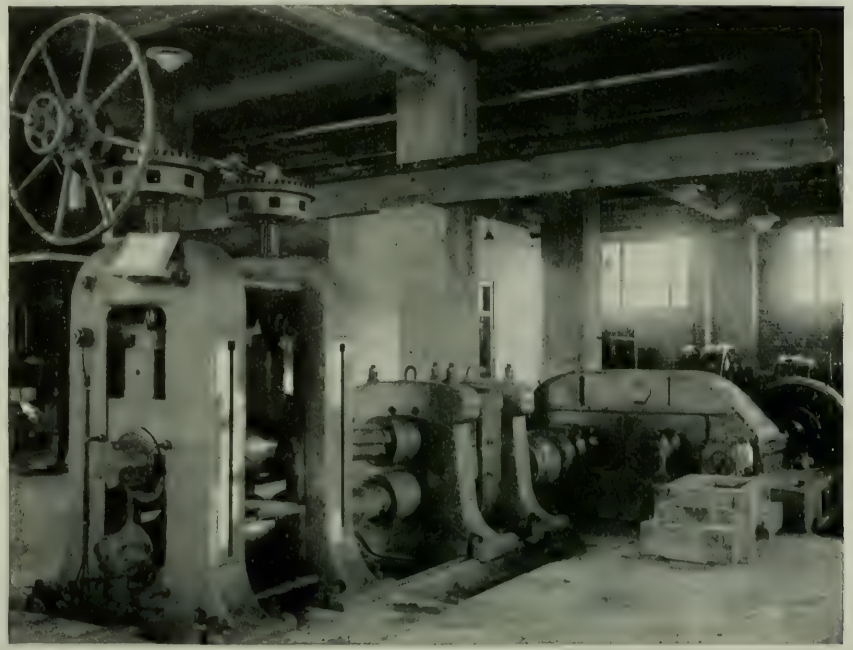

FIG. 1.—*Two high 16-inch plate mill (of the Bureau of Standards) in which the ingots were rolled*

MANUFACTURE AND PROPERTIES OF STEEL PLATES CONTAINING ZIRCONIUM AND OTHER ELEMENTS

By George K. Burgess and Raymond W. Woodward

ABSTRACT

This paper describes the manufacture and certain physical properties obtained from steel plates produced from about 193 heats of steel containing in various combinations the following principal variable elements: Carbon, silicon, nickel, aluminum, titanium, zirconium, cerium, boron, copper, cobalt, uranium, molybdenum, chromium, and tungsten.

None of the steels presented any difficulties in rolling into plate except those containing boron. Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron, which is fusible at the temperatures ordinarily used in rolling, but at slightly lower temperatures steel containing boron can be rolled successfully.

The usual mechanical and impact tests were carried out on all of the steels. It is shown that steel containing 0.40 to 0.50 per cent carbon, 1 to 1.50 per cent silicon, 3 to 3.25 per cent nickel, and 0.60 to 0.80 manganese and deoxidized with a simple deoxidizer, such as aluminum, can be produced having a tensile strength of approximately 300 000 lbs./in.^{2} with excellent ductility and toughness. This type of steel is recommended for a structural material.

Although the same high properties are obtained in steels of the above composition with the aid of additional elements, it does not appear necessary in general, to resort to such additions of more costly alloying elements.

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I. INTRODUCTION

This investigation originated in the need of the ordnance departments of the Army and Navy for information regarding the effects on the ballistic properties of light armor plate of certain chemical elements, such as zirconium, on the one hand, and the effects of such elements as uranium in reducing erosion in guns, on the other hand. The account here given relates mainly to the efforts to produce armor plate of various compositions.

After conference with the representatives of the several establishments interested, a joint program was outlined according to which the Bureau of Mines was to produce and analyze ingots of the desired compositions, the Bureau of Standards to manufacture and heat treat plates, carry out physical tests, microexaminations and chemical analyses, and develop methods of chemical analysis when needed for the more unusual elements in steel, and the Navy Department was to carry out the ballistic tests.

The most urgent problem was the determination of the effect of zirconium on the properties of carbon steels and of nickel-carbon steels, and especially to differentiate between the effects of zirconium and silicon.

As the work progressed it was considered desirable to investigate the effects of other elements, and there were accordingly included steels containing titanium, aluminum, boron, molybdenum, cerium, cobalt, chromium, vanadium, tungsten, uranium, and copper.

In addition to the ingots furnished by Dr. Gillett, opportunity was given to examine plates of steel containing zirconium manufactured by an automobile manufacturer.

Although the results of the ballistic tests are not available for publication, an account of the mechanical properties and tests of this series of somewhat unusual steels is considered worthy of consideration. The nickel-silicon group appears to be of particular interest, as is also the fact brought out that zirconium does not appear to confer any especially advantageous properties to types of steel here studied, and, in fact, behaves very much like silicon, although for carbon steels the data are not sufficiently complete to warrant conclusions.

The investigation throws some additional light on the manner in which certain of the rarer elements enter into steel, and there were also developed new analytical methods for the determination of zirconium in steels and of several of the unusual elements in the presence of each other.

II. COMPOSITION OF INGOTS

The chemical composition of all ingots was determined from drillings taken from both the top and bottom of the ingots. From each of these sets of drillings an analysis was made for all the elements occurring in the steel by Dr. Gillett and his associates at Ithaca. Samples were also taken from the top and bottom crops at the Bureau of Standards and further analysis made for the aluminum, titanium, and zirconium content.[1] Since the exact determination of this combination of elements presents some difficulty, the method used at the Bureau is included in the appendix.[2]

The composition of the various ingots will be found in Tables 11 to 22, while Table 1 gives a list showing in which table the data for a given heat appears. The analytical values for carbon, silicon, manganese, nickel, and other alloying elements are as reported by Dr. Gillett. Those for aluminum, titanium, and zirconium are a weighted mean of the determinations made at the Bureau of Standards and by the Bureau of Mines. In case the top and bottom samples showed segregation to have occurred in the ingot the values for both top and bottom are given in the table. No determinations were made of the sulphur or phosphorus content except in the few cases noted, since the steels were made from Armco iron as a base, and it is believed that these steels will run below 0.035 per cent sulphur, except 1256 and 1257, in which it was intentionally raised, and below 0.015 per cent phosphorus.

[1] These determinations were made under the direction of Dr. G. E. F. Lundell.

[2] See also Lundell and Knowles, Jl. Ind. and Eng. Chem., 12, p. 562, 1920; The determination of zirconium in steel.

In addition all will contain about 0.04 per cent copper and probably a small amount of cobalt, carried in by the commercial nickel, in the steels containing nickel.

TABLE 1.—List Showing Tables in Which Composition and Mechanical Properties of Various Heats May be Found

Heat No.	Table No.	Heat No.	Table No.	Heat No.	Table No.	Heat No.	Table No.
1101	13	1163	11	1204	12	1243	14
1102	11	1164	11	1205	12	1244	22
1103	13	1165	12	1206	12	1245	12
1104	11	1166	12	1207	20	1246	12
1105	13	1167	12	1208	12	1247	14
1106	13	1168	12	1209	12	1248	14
1107	13	1169	12	1210	14	1249	14
1109	13	1170	12	1211	14	1250	14
1111	14	1171	12	1212	14	1251	12
1112	14	1172	12	1213	14	1252	15
1113	12	1173	20	1214	12	1253	15
1114	12	1174	12	1215	12	1256	15
1115	14	1175	14	1216	12	1257	15
1117	14	1176	14	1217	12	1258	15
1118	12	1177	22	1218	14	1259	15
1119	14	1178	22	1219	14	1260	15
1120	12	1180	13	1220	14	1261	17
1128	12	1181	13	1221	14	1263	17
1129	12	1182	13	1222	14	1264	17
1130	12	1183	13	1223	14	1267	17
1131	14	1184	13	1224	14	1268	15
1132	14	1185	13	1225	14	1269	11
1133	14	1186	14	1226	12	1270	11
1134	14	1187	14	1227	12	1271	20
1135	18	1188	14	1228	22	1272	15
1136	18	1189	14	1229	22	1273	20
1138	14	1190	14	1230	14	1274	17
1144	14	1191	14	1231	14	1275	17
1145	14	1192	14	1232	14	1276	17
1146	14	1193	14	1233	14	1277	17
1147	12	1194	14	1234	14	1278	17
1155	19	1195	14	1235	14	1279	16
1156	19	1196	14	1236	12	1280	16
1157	14	1197	14	1237	12	1281	15–16
1158	14	1198	11	1238	12	1282	16
1159	14	1199	11	1239	12	1283	16
1160	14	1200	11	1240	14	1285	16
1161	14	1201	11	1241	14	1286	16
1162	14	1202	12	1242	12	1289	14

Heat No.	Table No.
1290	14
1291	14
1292	14
1293	14
Comparison steels	
1	14
2	14
3	18-21
4	18
5	19
6	18
7	14
8	14
9	18
10	14
11	14–18
12	19
13	12
14	14–21
15	18–21
16	14
17	14
18	14
19	19
20	14
21	14
22	21
23	20
24	14
25	14
26	14
27	14
28	12

III. PREPARATION OF PLATES AND TEST PIECES

1. CROPPING AND ROLLING OF INGOTS

The ingots after having been made at the Bureau of Mines Experimental Station at Ithaca, N. Y., as described in a forthcoming paper of the Bureau of Mines, were shipped to the Bureau of Standards and there rolled into plates.

(a) DESCRIPTION OF INGOTS

The first ingots received were plain, round ingots without hot tops, cast large end up, the length being about 15 inches, top diameter about 3½ inches, and bottom diameter about 2½ inches.

This series, embracing Nos. 1101 to 1120, naturally contained a large pipe or cavity at the upper end, and a top crop of about 5 inches was necessary to remove physically unsound material.

Bottom crops on this series (except Nos. 1118 and 1120) had been taken previous to receipt at the Bureau of Standards. No crops were taken on ingot Nos. 1101–1104, 1109, 1111, and 1114 at the Bureau, as these ingots had been machined down on the ends and surface before shipment.

Ingots from No. 1128 to 1158 were also of the same general dimensions and form as the previous ones, but with the addition of a hot top of about 2¼ inches diameter. Most of this top had been knocked off while the ingot was still hot, directly after stripping from the mold. The tops of these ingots were cropped just below the junction of the hot top with the body of the ingot, or slightly farther in a few cases, to insure sound material. The bottom crop was just sufficient to remove the rounded end of the ingot.

The remainder of the ingots were square in cross section, about 3 inches at the top and 2½ inches at the bottom. The length, exclusive of the hot tops, was about 21 inches. The average weight of these ingots was 41.5 pounds before cropping and 35 pounds when ready to roll. The length after cropping was about 18 inches.

Table 2 gives a summary of the weight of ingots and crops for the various types of the ingots and also the percentage available for rolling after having been cropped. The data show remarkably well the advantage to be gained by the use of a hot top, the available material without such means being about 65 per cent, while with a hot top the average was 84 per cent. This latter figure should be slightly reduced (possibly 5 per cent) to allow for a portion of the hot top having been knocked off at Ithaca. This corrected figure, however, agrees very well with similar data obtained on 4½-ton ingots and reported elsewhere,[3] especially when the small size of the ingots used in this investigation is considered.

(b) ROLLING DATA

The ingots were rolled in a two-high 16-inch plate mill, a photograph of which is shown in Fig. 1. This mill is driven by a 150-horsepower 230-volt direct-current motor and is nonreversing.

[3] Steel Rails from Sink-Head and Ordinary Rail Ingots, by George K. Burgess, Bureau of Standards Technologic Paper, No. 178

The motor speed is variable from 250 to 1000 revolutions per minute, which with the reduction gear gives a roll speed of 20 to 80 revolutions per minute. For this work the roll speed was kept constant at the lowest value, corresponding to a peripheral velocity of approximately 83 feet per minute.

The heating of the ingots was by means of a gas-fired semi-muffle furnace. Usually about 10 ingots were rolled at one heating, and they were charged into the cold furnace and brought to temperature with the furnace. With the exception of those steels containing boron, which are discussed later, the furnace temperature was maintained at from 1100 to 1150° C. The ingots were rolled until their temperature had fallen to about 850° C. This temperature was checked in many cases by means of an optical pyrometer. The ingots were then reheated and the operation repeated.

All of the ingots were first squared down to 2½ inches square in four passes by turning the ingot through a 90° angle at alternate passes. This gave a maximum reduction of about 10 per cent per pass.

Ingots up to 1163 were then cross rolled until 6 to 7 inches wide and then rolled lengthwise until ½ inch thick. The average size of finished plate was about 28 by 6½ by ½ inch. A total of about 40 passes was required, with about 5 per cent reduction per pass. The other ingots were entirely cross rolled after squaring, producing plates of various sizes, usually about 20 by 13 by ½ inch (or ⅜ inch).

It is probable that the percentage reductions per pass could be considerably increased, but since the rolling properties of the majority of the ingots were unknown it was deemed advisable to have a considerable margin of safety. A portion of those ingots which were rolled into long narrow plates (1101 to 1162) was cut off and rerolled to ⅜ inch thickness.

TABLE 2.—Average Ingot Weights

Ingot Nos.	Original weight	Top crop	Bottom crop	Cropped ingot	Available for rolling	Loss in rolling
	Pounds	Pounds	Pounds	Pounds	Per cent	Per cent
1101–1120	34.5	12.0	.....	21.2	64.9	3.1
1128–1158	34.5	5.9	1.5	27.1	79.8	2.3
1159–1293	41.5	4.8	1.8	35.0	84.2	1.9
Average of all	40.5	5.3	1.7	32.7	82.4	2.0

(c) DISPOSITION OF MATERIAL

The plates from ingots 1101 to 1162 were sawed similar to sketch of Fig. 2, which represents plate No. 1129, although typical of all. *AB* and *GF* were plates for ballistic tests, *BC* and *CD*

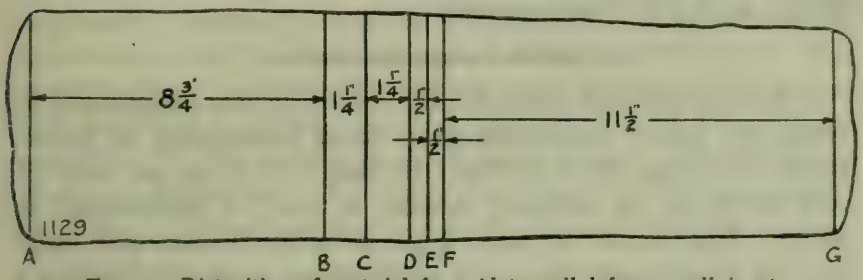


FIG. 2.—*Disposition of material from plates rolled from small ingots*

each about 1 inch wide, were for tensile specimens, *EF* for microscopic examination and thermal analyses, while the remaining small pieces were held in reserve. The lengths of the two plates were so adjusted that the rerolled portion would be the same length as the unrolled portion.

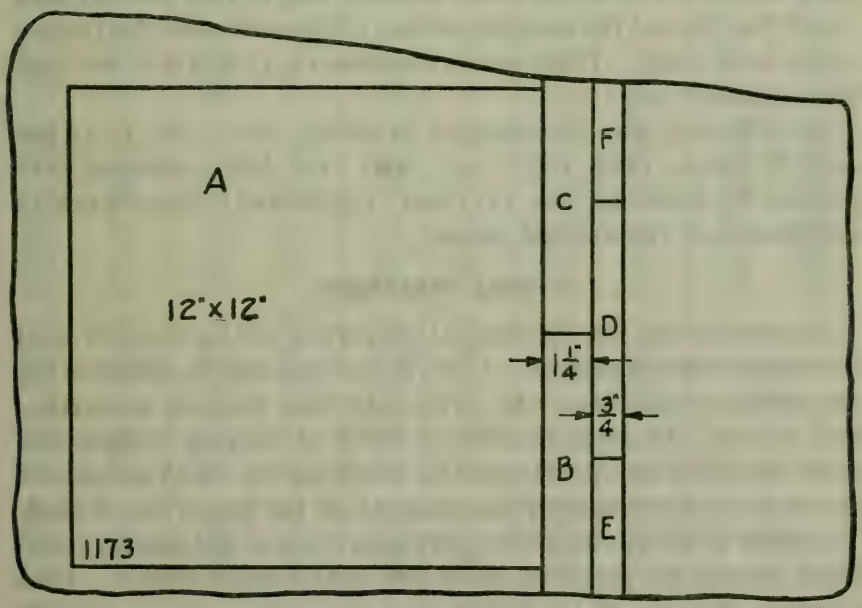


FIG. 3.—*Disposition of material from plates rolled from large ingots*

From the later plates (1163 to 1293) a single ballistic test piece was cut 12 by 12 inches, or as large as possible, if the ingot was too small to permit of this dimension. The other test pieces were taken then as shown by the typical diagram for plate No. 1173 in Fig. 3. *A* is the ballistic plate, *B* and *C* tensile specimens,

D for impact sample, and *E* and *F* for microscopic examination and thermal analyses, respectively. Any plates which were not perfectly flat were straightened at a temperature of about 800° C by means of a hydraulic forging press. The plates were not pickled until after heat treatment.

(d) INGOTS CONTAINING BORON

As was anticipated, considerable difficulty was experienced in rolling the ingots containing even small percentages of boron. Ingots Nos. 1254 (0.73 per cent B) and 1255 (0.30 per cent B) were heated in the ordinary manner to 1100° C preparatory to rolling. Upon removing these ingots from the furnace with tongs they fell apart under their own overhanging weight, furnishing a striking example of hot-shortness. No. 1262, containing 0.46 per cent boron, was heated to only 960° C and likewise broke after partial rolling. Nos. 1261, 1263, and 1264 were similarly heated and were rolled satisfactorily, although containing 0.71, 0.23, and 0.46 per cent boron, respectively. Nos. 1265 and 1266 were partially rolled, but broke up under the rolls and, in fact, were so hard to roll that two of the coupling collars of the mill were also broken at the same time. These ingots contained 0.23 and 0.46 per cent boron, respectively.

No difficulty was encountered in rolling Nos. 1267 (0.44 per cent B), 1274, 1275, 1276, 1277, and 1278 (all containing 0.10 per cent B), although Nos. 1274 and 1276 showed numerous cracks and fissures in the finished plates.

2. HEAT TREATMENT

In determining the mechanical properties of the series of steel two needs were considered. First, it was desirable to correlate the mechanical properties of the steels with their ballistic properties; and, second, the large number of steels of varying composition made available an opportunity for studying the effect of some of the more uncommon alloying elements on the properties of steel. To satisfy properly the first requirement, tensile and impact specimens should be prepared from the heat-treated plates. This, however, because of the hardness of the plates, was practically impossible to carry out without what seemed to be unwarranted expense and time. For the second requirement it would be preferable to make tests on a series of specimens from each composition drawn back to various temperatures after quenching from the proper temperature. This, again, would have required con-

siderable additional work; and, moreover, there was not enough material to make a complete survey of the entire tempering range.

A compromise was accordingly effected whereby tensile tests were made on normalized and heat-treated specimens cut from the plates before heat treatment, as noted in Section III, 1 (*c*). The heat treatments were similar for all compositions of the series. That is, after normalizing and quenching in oil each from a temperature 30° C above the end of the upper critical range the specimens were drawn back at a temperature 175° C for three hours, this being the same treatment given the plates for ballistic testing.

TABLE 3.—Normalizing and Hardening Temperatures

[All temperatures in °C]

No.	Temp.	No.	Temp.	No.	Temp.	No.	Temp.	No.	Temp.
1101	840	1159	780	1195	840	1231	800	1271	780
1102	860	1160	780	1196	860	1232	780	1272	820
1103	825	1161	840	1197	860	1233	780	1273	820
1104	840	1162	780	1198	900	1234	840	1274	820
1105	810	1163	860	1199	900	1235	860	1275	840
1106	860	1164	860	1200	820	1236	840	1276	760
1107	860	1165	820	1201	840	1237	840	1277	800
1109	800	1166	860	1202	860	1238	800	1278	850
1111	770	1167	780	1204	840	1239	800	1279	760
1112	790	1168	840	1205	820	1240	800	1280	780
1113	770	1169	820	1206	820	1241	780	1281	780
1114	770	1170	780	1207	800	1242	800	1282	800
1115	780	1171	860	1208	800	1243	800	1283	780
1117	860	1172	860	1209	800	1244	820	1285	820
1118	785	1173	840	1210	860	1245	820	1286	800
1119	810	1174	840	1211	860	1246	800	1289	800
1120	820	1175	840	1212	800	1247	840	1290	820
1128	820	1176	820	1213	800	1248	880	1291	780
1129	840	1177	860	1214	820	1249	800	1292	780
1130	820	1178	860	1215	800	1250	920	1293	800
1131	830	1180	860	1216	820	1251	820		
1132	830	1181	860	1217	800	1252	800		
1133	820	1182	860	1218	820	1253	805		
1134	820	1183	860	1219	820	1256	840		
1135	780	1184	900	1220	800	1257	840		
1136	780	1185	900	1221	820	1258	780		
1138	805	1186	900	1222	780	1259	780		
1144	820	1187	900	1223	780	1260	820		
1145	820	1188	900	1224	820	1261	880		
1146	780	1189	900	1225	820	1263	880		
1147	790	1190	860	1226	840	1264	820		
1155	805	1191	860	1227	840	1267	880		
1156	805	1192	860	1228	800	1268	840		
1157	810	1193	860	1229	820	1269	840		
1158	780	1194	840	1230	760	1270	840		

The normalizing and hardening treatments for the small-test specimens were carried out in a small electric muffle furnace; the specimens were placed in the cold furnace, brought to the desired temperature with the furnace, and held at that temperature for 15 minutes. The normalized specimens were

allowed to cool in the air, and the specimens to be hardened were quenched in the oil at room temperature. In Table 3 are given the common normalizing and quenching temperatures. For tempering, the specimens were heated in an oil bath to 175° for three hours and allowed to cool in the air after removing from the bath.

The duplicate tensile specimens from each plate were, in general, normalized at the same time, and then one of them hardened and tempered and the other kept in the normalized condition.

The ballistic plates were heat treated in a manner similar to that used for the test specimens, except that larger furnace units were required and the plates were held at the desired temperatures for 45 minutes before withdrawing from the furnace.

IV. PROPERTIES OF THE MATERIAL

1. CRITICAL RANGES

In order to prescribe properly the heat treatment of the various steels, the critical ranges of several of them were determined, particularly those containing the more unusual elements, such as zirconium, boron, cerium, copper, and large amounts of silicon. Inverse rate curves were obtained on samples of 1.5 to 2.0 grams mass by means of a modified Rosenhain furnace.[4]

The temperature measurements were taken with a platinum, 90-platinum 10-rhodium thermocouple. The rate of heating and cooling was approximately 0.20° C per second, while the maximum temperature to which the specimen was carried varied between 840 and 920° C.

Table 4 gives the results obtained, together with the composition of the materials investigated. Although the end of the Ac_{2-3} transformation is all that is needed to determine the proper heat treatment, the other values are included as a matter of interest. For comparison there are also shown in the table data for a plain carbon and a 3 per cent nickel steel, both of which contain the other elements within commercial limits.

[4] Scott and Freeman, Bull. Am. Inst. of Min. and Met. Eng., No. 152, p. 1429; August, 1919. Also Bureau of Standards Scientific Paper, No. 348.

TABLE 4.—Critical Ranges of Representative Material

[All temperatures in ° C]

No.	Composition								Ac_1			Ac_{2-3}		Ar_{3-2}		Ar_1		
	C	Si	Mn	Ni	Al	Ti	Zr	Other elements	Beg.	Max.	End	Max.	End	Beg.	Max.	Beg.	Max.	End
1101	0.51	1.15	0.80	.....	0.09	0.04	0.10	.....	755	759	778	.....	780	745	716	695	690	678
1102	.36	1.15	.65	.....	.03	.06	.....	.....	750	754	770	.....	842?	784	755	684	677	668
1104	.39	.66	.58	.....	.01	.03	.....	.....	732	738	756	.....	820?	773	751	682	676	664
1105	.56	.54	.75	.....	.07	.02	.09	.....	741	747	759	768?	778	730	710	688	683	670
1106	.42	.44	.55	.....	.13	.01	.15	.....	737	742	759	.....	828	755	731	690	683	671
1107	.37	.73	.50	.....	.02	.03	.20	.....	745	753	766	797?	843	798	775	696	690	680
1109	.47	.85	.78	.....	.15	.02	.11	.....	748	753	768	788	808	749	718	692	686	668
1111	.46	.27	.59	3.15	.03	.01	.03	.....	697	703	.....	.....	739	659	636	615	605	577
1112	.46	1.10	.66	2.95	.09	.03	.08	.....	720	725	.....	.....	758	646	.....	.....	613	588
1113	.55	1.15	.76	3.55	.03	.03	.....	.....	711	716	.....	.....	738	658	.....	.....	613	578
1114	.49	.52	.65	3.25	.02	.03	.....	.....	701	705	.....	.....	736	643	.....	.....	611	572
1133	.39	1.65	.75	3.30	.01	.02	.30	.....	719	733	746	.....	778	671	641	616	605	594
1135	.42	1.45	.83	3.25	.01	.....	.....	Mo 0.78	.....	720	751	.....	.....	.....	.....	477	426	.....
1255	.38	1.00	.75	2.90	.....	.....	.....	B .30	719	725	741	776	782	658	640	620	617	588
1262	.16	1.30	.64	2.80	.....	.....	.....	B .49	.....	739	745	795	817	701	685	622	613	590
1272	.40	.27	.69	.....	.....	.....	.....	Ce .35	732	737	.....	777	793	738	722	699	684	668
1274	.45	.33	.69	.....	.03	.....	.....	B .06	734	738	760	778	785	734	714	694	690	675
1279	.58	.23	.90	2.45	.01	.....	.....	Cu .62	682	697	.....	714	725	628	616	611	603	547
COMPARISON STEELS[a]																		
C 24	0.40	0.22	0.75	.....	.....	.....	.....	.....	726	732	748	783	802	743	729	681	672	654
A 51	.40	.28	.63	2.90	.....	.....	.....	.....	686	701	714	726	743	670	644	617	606	572

[a] These values are taken from Bureau of Standards Scientific Papers, No. 376.

By comparing C 24, 1104, and 1102, containing, respectively, 0.22, 0.66, and 1.15 per cent silicon, it will be noticed that silicon progressively raises the Ac ranges and the Ar_{3-2} range. The Ar_1 point is also raised, but not to so great an extent as the other values. This effect is also the same in the presence of nickel, as shown by Nos. 1111 and 1112.

Zirconium has about the same effect on the critical ranges as silicon, as will be observed from an inspection of the several data.

The effect of cerium is apparently rather small and irregular, as will be seen from Nos. C24 and 1272. The Ac_1 and Ar_1 points are raised somewhat and the Ac_{2-3} and Ar_{3-2} points decreased by about a similar amount.

Copper evidently produces the same result upon the critical ranges as an equal amount of nickel, No. 1279 having values that would be expected for a 3 per cent nickel steel with 0.58 per cent carbon.

In specimen No. 1135, containing 0.78 per cent of molybdenum, the Ac_1 range is about normal for a steel of similar composition but without the molybdenum, whereas the Ar_1 range has been considerably depressed, as has also been observed by other investigators.

From Nos. 1255, 1262, and 1264, containing boron in amounts from 0.06 to 0.49 per cent, and by comparison with Nos. C 24 and 1133, keeping in mind the variations in composition, it appears that boron raises all of the ranges somewhat.

2. MICROSTRUCTURE

(By S. Epstein)

It must be assumed that if zirconium or any of the other elements that were used are to have any virtue as additions to light armor-plate steels they should exert some noticeable effect on the microstructure of these steels at least in some stage of the heat-treated state, if not in the annealed condition. Also, if any true comparisons are to be drawn between steels of different chemical compositions from tests of their mechanical properties, it is plainly essential to know that the tested specimens have all been treated alike, or, if there are differences in the treatments, to know where they occur. It was the object, therefore, in the microscopic examination first to determine the rôle played by the zirconium, as well as the other addition elements in the steels, and, second, to examine the plates and test specimens for variations in soundness and heat treatment.

(a) ZIRCONIUM, TITANIUM, ALUMINUM

A steel containing zirconium can at once be recognized under the microscope by the presence of bright-yellow square inclusions not plainly visible at magnifications lower than 500 diameters (see Fig. 4). They are not affected by the ordinary alcoholic nitric or picric acid etching solutions, but retain their lustrous yellow color. In the steels examined these yellow inclusions were generally associated with orange-pink square inclusions and irregularly shaped purplish-gray ones. By a comparison of the chemical compositions of the steels the orange-pink ones were traced to the presence of titanium, while the purlpish-gray ones are probably due to alumium. However, this last point could not be established as positively as with the yellow and orange-pink inclusions (see Fig. 5). All of the inclusions manifested a tendency to form groups of tiny segregates, which when rolled, flattened out to thin plate-like streaks (see Fig. 6). These plates could readily be seen with the naked eye in the polished and etched specimens as yellow streaks. They could be noticed, also, in the fractures of some of the tested tension bars and impact specimens as laminations. In the specimens containing zirconium and titanium in which cracks were found the inclusions were most numerous very close to the cracks. Very few of the inclusions were found outside the segregates and streaks or away from the cracks.

Except for the bright-yellow square inclusions, which persisted throughout the working of the steel, the presence of zirconium was not found to affect the microstructure of the steels in any respect. Although the steels examined were regarded for the most part as alloy steels, the majority of the series under the microscope looked like plain carbon steels (see Fig. 7). In the air-cooled specimens it was considered that if any martensite or troostite were found it must be attributed to a self-hardening property or retardation of the Ar_1 transformation produced by the alloying elements. Otherwise, the structure would consist of granular pearlite and sorbite. Many of the other steels, to be referred to later (see Fig. 8), did show some martensite and troostite in the normalized specimens; but in no case was the presence of martensite or troostite in air-cooled specimens found to be due to zirconium. It may be that not all of the zirconium goes to form the characteristic yellow squares and that some of it goes into solution in the steel; but in that case it does not have a marked effect on the microstructure. In this

respect it may be likened to silicon, which goes into solution but the presence of which in small amounts can not be detected under the microscope. Thermal analyses seem to indicate that part at least goes into solution. Titanium and aluminum also formed characteristic inclusions, but otherwise gave no sign of their presence under the microscope.

The yellow square inclusions are very hard, but because they make up such a small proportion of the mass of the steel it can scarcely be conceived that they can exert a very great influence on its mechanical properties. The fact that they are associated in the form of segregates is a disadvantage, especially in an armor-plate steel. Wherever cracks were found in steels containing zirconium the yellow inclusions were most numerous near the cracks, and the conclusion that the cracks are in some way associated with the plates of inclusions appears to be warranted. The yellow inclusions of zirconium are very similar to the orange-pink ones of titanium, and with regard to the tendency of the former to segregate and form its negative effect on the microstructure it may also be compared to titanium, which is regarded as a scavenger and not a true alloying element. In general, zirconium, titanium, and aluminum may all be put in one class. They appear to act primarily as scavengers, and when they are not removed as part of the slag are present in the steel in the form of inclusions. They may go into solution in the steel, but in that case their presence can not be detected in the microscope and their effect would appear to be slight or negligible. In the form of inclusions they can not do much good, and if these are segregated and rolled out into thin plate-like streaks they may be detrimental.

(b) OTHER ALLOYING ELEMENTS

In contrast to zirconium, titanium, and aluminum, the other additions to the steels may be regarded as true alloying elements. Carbon, silicon, manganese, and nickel were not considered as special additions in this respect, and while their presence in the course of the examination was always noted they were not under particular observation. The other alloying elements may be grouped as follows: (1) Chromium, tungsten, vanadium, molybdenum; (2) cerium, uranium; (3) copper; (4) boron.

The first four—chromium, tungsten, vanadium, and molybdenum—go into solution and produce a martensitic pattern in the air-cooled specimens (see Fig. 8, *a*, *b*, *c*, *d*). Cerium and uranium go into solution and produce a martensitic pattern in the

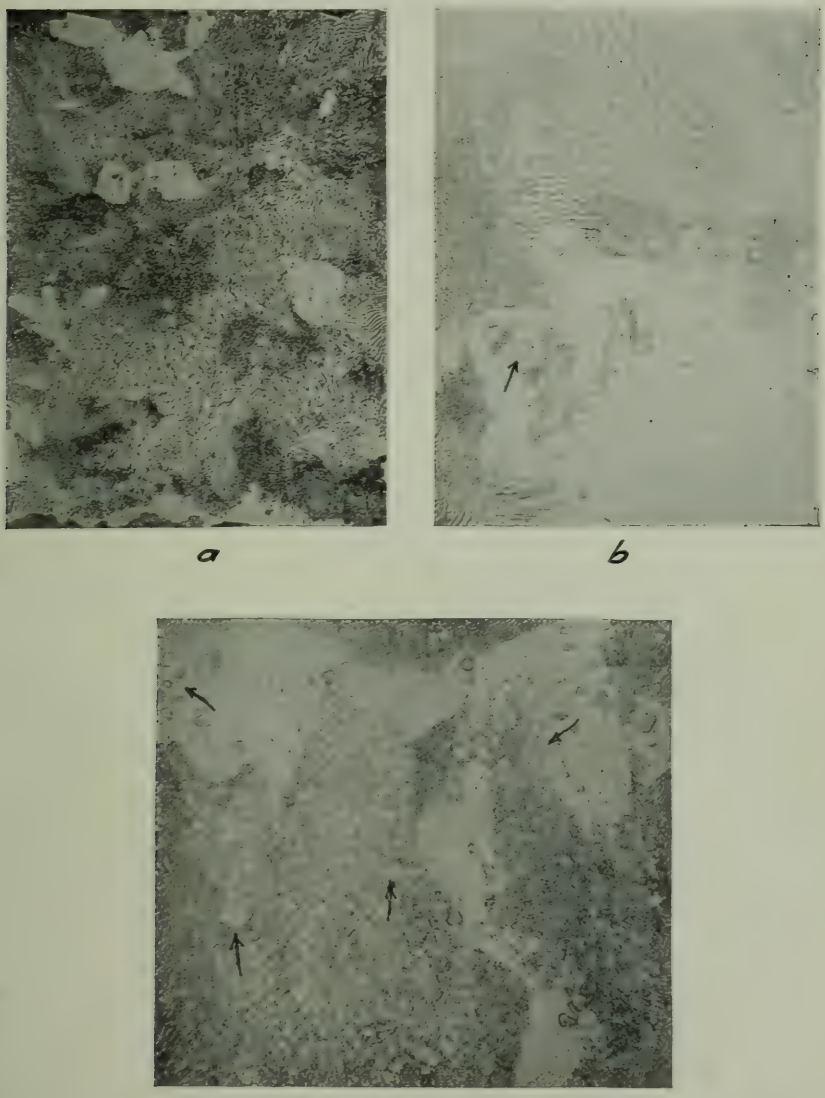


FIG. 4.—*Inclusions in ingot 1109 as cast containing 0.11 per cent zirconium. Etching, 2 per cent nitric acid*

(*a*) The bright yellow inclusions can not be distinguished at this magnification. ×100
(*b*) This spot shows the average number of inclusions which are indicated by the arrows. They are bright yellow in color. ×500
(*c*) A segregate of the bright yellow square inclusions is here shown. Most of these inclusions are segregated in this way. ×500

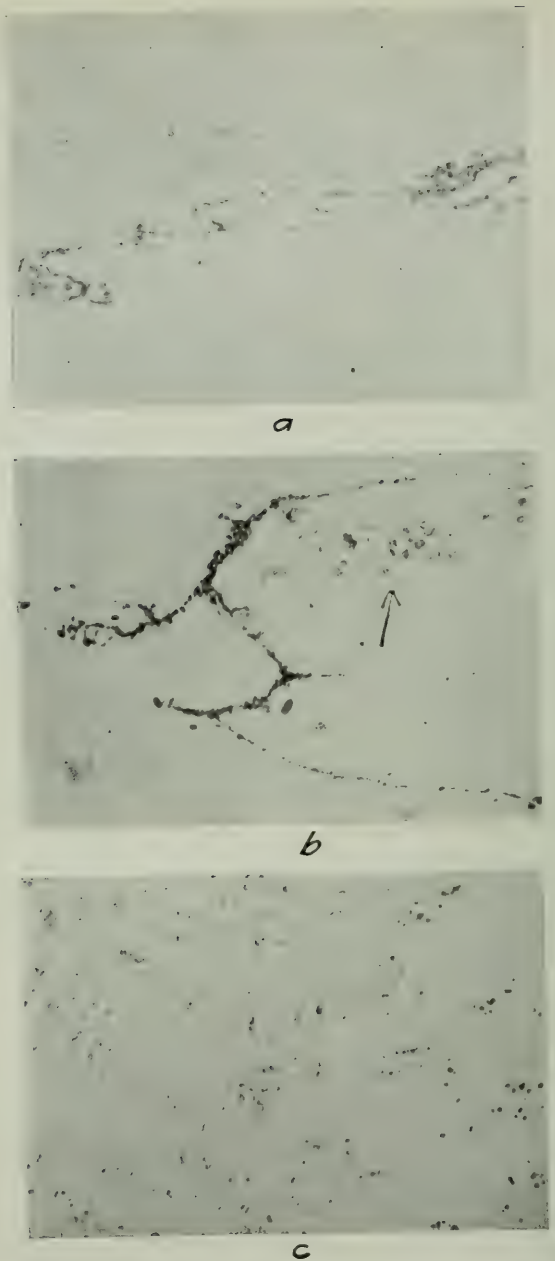


FIG. 5.—*Different types of inclusions found in the steels. Not etched. Magnification* ×500

(*a*) Steel 1158. Al, 0.173 per cent; Ti, 0.028 per cent; Zr, 0.22 per cent. Of the square inclusions some are bright yellow and some are orange-pink. The yellow inclusions are due to zirconium, the orange-pink to titanium. The circular inclusions arranged in a threadlike continuity are purplish gray in color and may be due to aluminum

(*b*) Steel 1176. Al, 0.25 per cent; Ti, 0.09 per cent; Zr, 0.11 per cent. A threadlike streak of the gray similar to (*a*) is to be seen. In the cluster of square inclusions indicated by the arrow the larger light-colored ones are bright yellow, the smaller darker ones are orange-pink

(*c*) Steel 1213. Ti, 0.04 per cent; Zr, 0.34 per cent. This shows a segregate of small yellow and orange-pink inclusions. Most of these inclusions are found in these segregates, very few outside

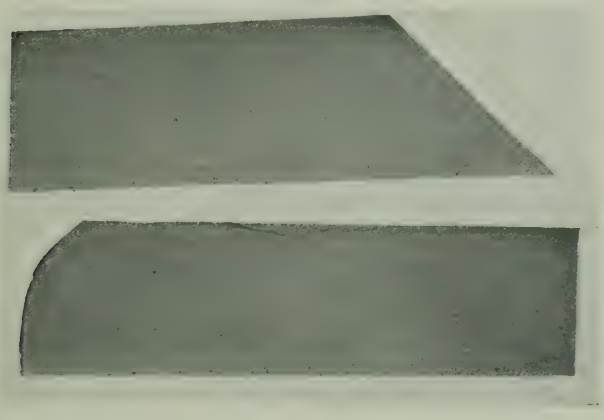


FIG. 6.—*Segregates of Ti and Zr inclusions rolled out into tin plate-like streaks*

Steel 1211, Butt—Ti, 0.07 per cent; Zr, 0.77 per cent. Top—Ti, 0.06 per cent; Zr, 0.92 per cent. The thin plates appear as yellow streaks easily visible to the naked eye in the polished and etched specimens. In the fractures of the impact and tension bars they look like laminations. Not etched. ×2

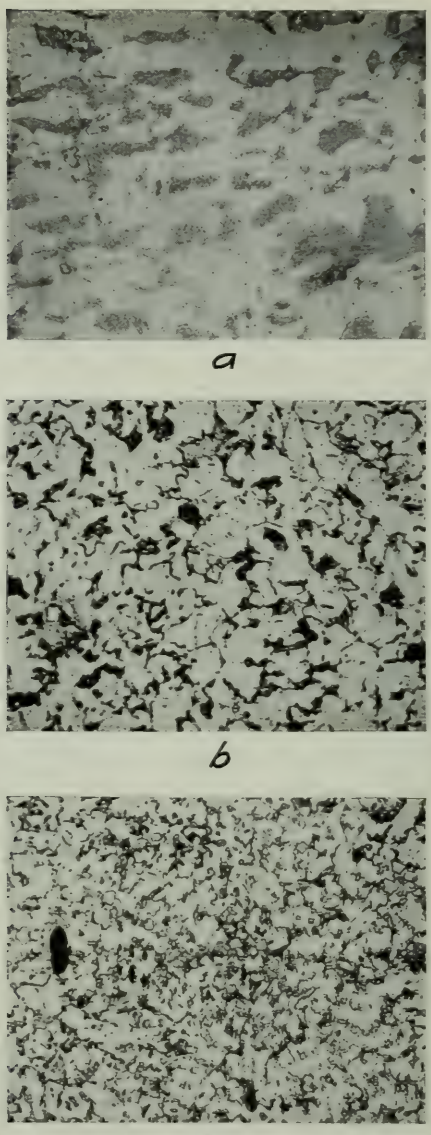


FIG. 7.—*Microstructure of air-cooled specimens of steel containing Ti and Zr. Etching, 2 per cent nitric acid; magnification, ×500*

(*a*) Steel 1185. C, 0.26 per cent; Ni, —; Al, 0.021 per cent; Zr, 0.30 per cent. The structure is granular pearlite and ferrite

(*b*) Steel 1186. C, 0.26 per cent; Ni, 2 per cent; Al, 0.013 per cent; Ti, 0.04 per cent; Zr, 0.24 per cent. The structure is again granular pearlite and ferrite. The structure is not essentially different from that of a steel containing a similar percentage of nickel but no other additions

(*c*) Steel 1225. C, 0.27 per cent; Ni, 3.04 per cent; Ti, 0.22 per cent; Zr, .034 per cent. The structure is granular pearlite and ferrite. In no case was the presence of Ti or Zr found to produce a martensitic pattern

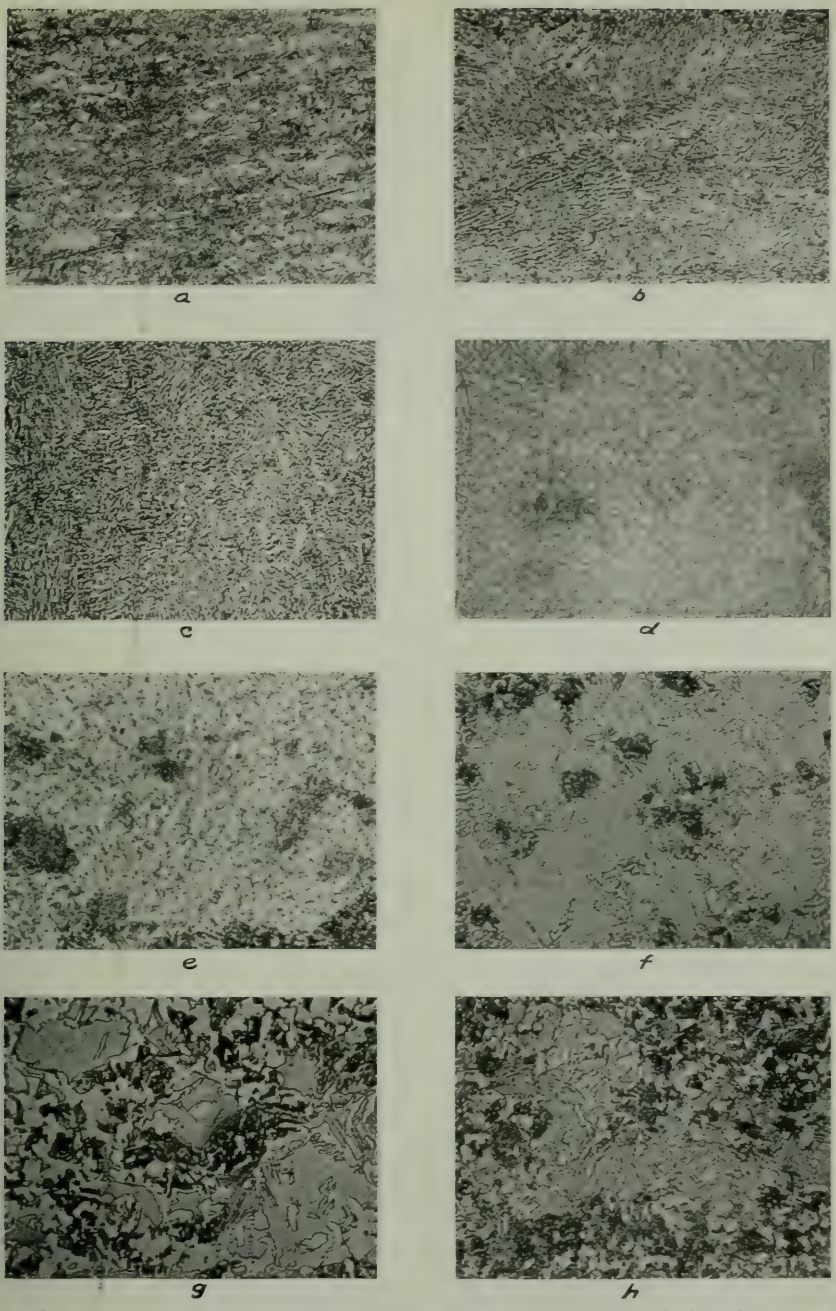


FIG. 8.—*Microstructure of air-cooled specimens containing other alloying elements. Etching, 2 per cent nitric acid; magnification,* $\times 500$

(*a*) Steel 1155. C, 0.38 per cent; Ni, 3.60 per cent; Cr, 1.14 per cent. The angular structure is typical of air-cooled nickel chromium steels
(*b*) Steel 1178. C, 0.32 per cent; Ni, 3.5 per cent; Cr, 2 per cent; W, 0.90 per cent. The angular structure is characteristic
(*c*) Steel 1207. C, 0.60 per cent; Ni, 3.6 per cent; Vd, 32 per cent
(*d*) Steel 1135. C, 0.41 per cent; Ni, 3.5 per cent; Mo, 0.78 per cent
(*e*) Steel 1258. C, 0.39 per cent; Ni, 2.65 per cent; Ce, 1.35 per cent. This steel displays a characteristic martensitic structure, due doubtless to the presence of the cerium
(*f*) Steel 1228. C, 0.63 per cent; Ni, 3.01 per cent; N, 0.52 per cent. The uranium has produced a martensitic pattern
(*g*) Steel 1226. C, 0.40 per cent; Si 1.61 per cent; M, 0.90 per cent; Ni, 3.04 per cent. The combination of high Si, Mn, and Ni has resulted in a martensitic pattern
(*h*) Steel 1282. C, 0.45 per cent; Si, 1.10 per cent; Mn, 0.84 per cent; Ni, 1.92 per cent; Cu, 1.35 per cent. The high percentage of copper had produced some martensite

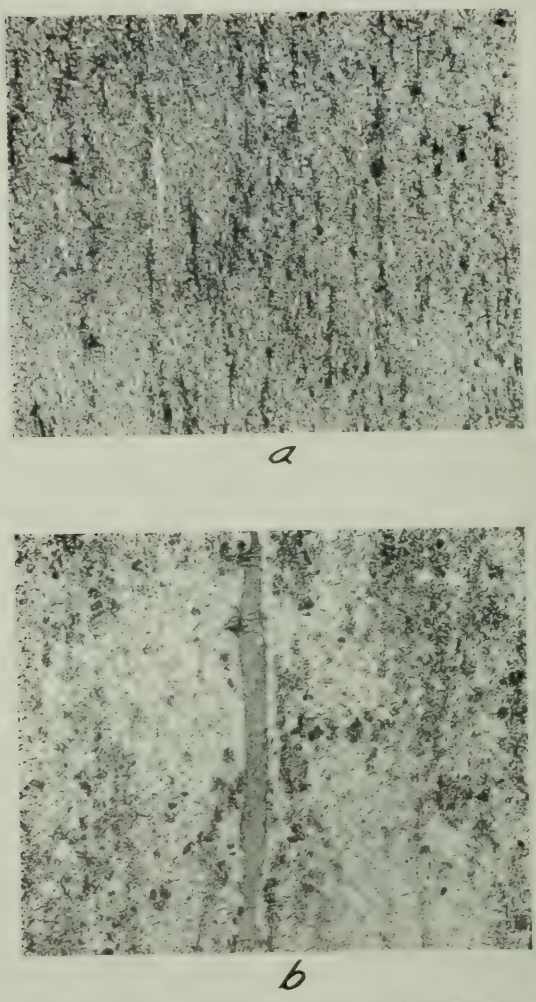
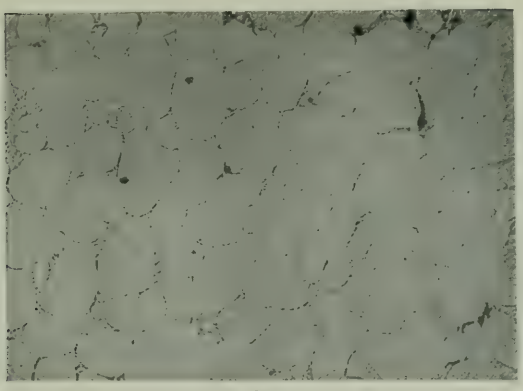


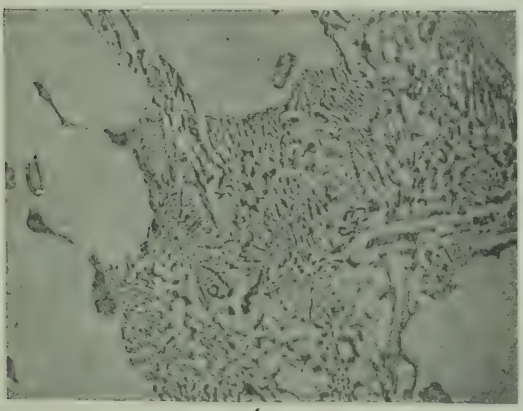
FIG. 9.—*Inclusions in cerium and uranium steels. Etching, 2 per cent nitric acid*

(*a*) Steel 1252. Air-cooled, Ce, 0.55 per cent. A large number of inclusions were segregated in streaks in this specimen. These streaks could be plainly seen with the naked eye. The shape and color of the inclusions can not be distinguished at the magnification of this micrograph, but at 500 diameters most of them appear as circular gray inclusions, while some are orange with gray markings inside the circumferences. The latter inclusions were found only in the cerium steels. ×50

(*b*) Steel 1228. Air-cooled uranium, 0.52 per cent. A large number of inclusions were segregated in this spot, together with the long slag inclusion shown here. At higher magnification it can be seen that the inclusions are circular and of a deep blue color. The typical angular structure resulting from the presence of uranium is especially noticeable in this segregated area. ×100



a



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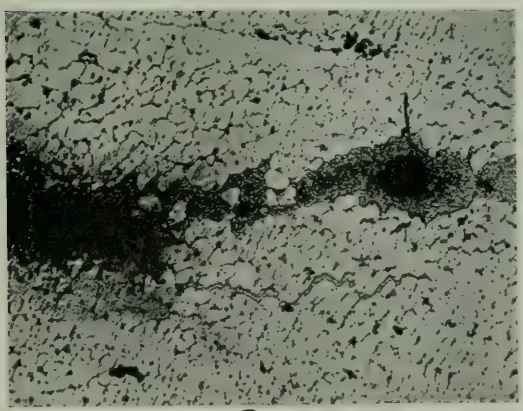


c

FIG. 10.—*Characteristic structure of boron steel*

(*a*) Steel 1262, containing 0.49 per cent B, which broke in the rolls. This shows the eutectic network. Not etched. ×100

(*b*) The eutectic etches dark with sodium picrate. This also shows where some of the eutectic has coalesced into the circular particles. Etching, sodium picrate. ×500

(*c*) The eutectic is fusible at the temperature ordinarily used in rolling. The cracks in the broken ingot all followed the network of the eutectic. This micrograph shows where a larger mass of eutectic has located a crack. Etching, sodium picrate. ×50

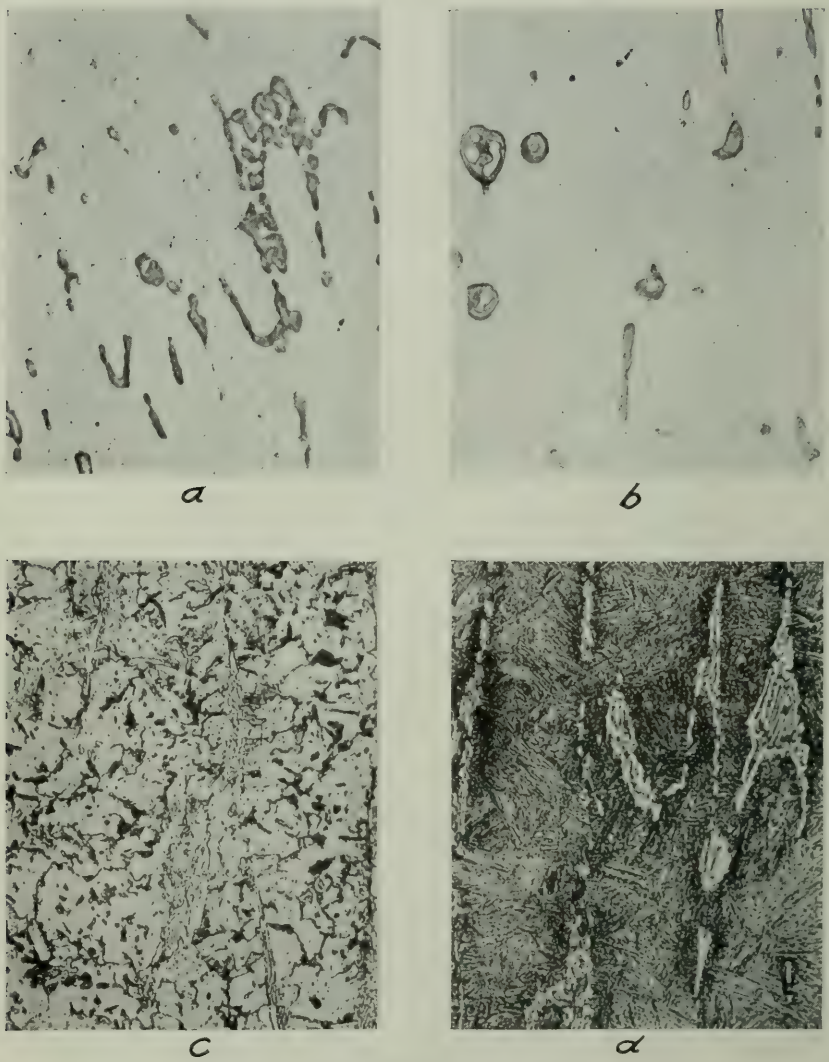


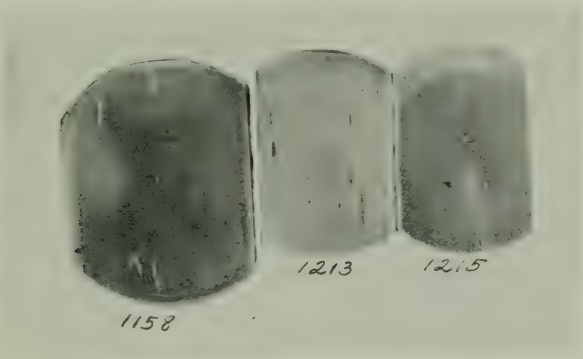
FIG. 11.—*Rolled and heat-treated steels containing boron,* $\times 500$

(*a*) Steel 1275. B, 0.08 per cent. This shows particles of the boron compound in the rolled and normalized specimen. Etching, sodium picrate

(*b*) Same steel as (*a*). This shows the particles of the boron compound in the quenched specimen. Etching, sodium picrate

(*c*) Steel 1263. B, 0.30 per cent. This is the air-cooled specimen. The white sharply outlined particles are the boron compound. Etching, 2 per cent nitric acid

(*d*) Same steel as (*c*), quenched. There are no definite circular and elongated particles, but a eutectic structure is present. This may be due to the fact that the specimen was quenched from a temperature high enough to allow the eutectic to form again. Etching, 2 per cent nitric acid



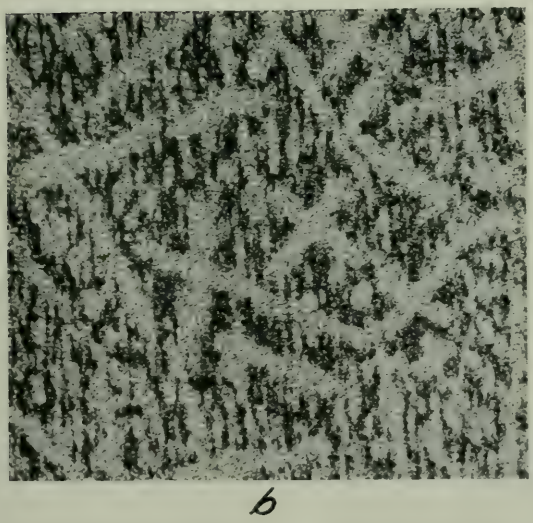
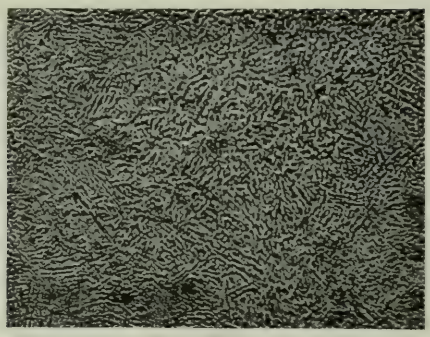


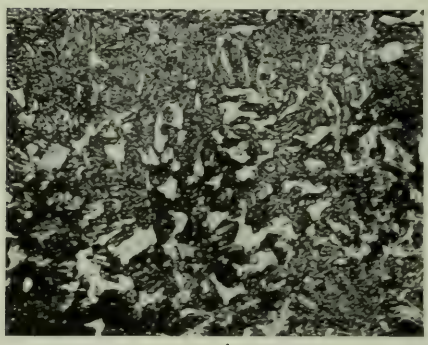
FIG. 12.—*Types of flaws existing in some of the steels. Etching, 2 per cent nitric acid*

(*a*) Steel 1158, H. T., cracked. Steel 1213, H. T., yellow streaks of titanium and zirconium inclusions. Steel 1215, H. T., dendritic. These specimens were taken from the shoulders of the tension bars. In the other steels that showed cracks the cracks were about the same size as in 1158, but there were not as many, generally one or two. ×1

(*b*) This shows the dendrites in Steel 1215, H. T., at higher magnification. ×50



a



b

FIG. 13.—*Influence of considerable amounts of ferrite on tensile properties of heat-treated specimens,* $\times 50$

(*a*) Steel 1144. C, 0.38 per cent; Si, 1.35 per cent; Mn, 0.84 per cent; Ni, 3.10 per cent; Al, 0.005 per cent; Ti, 0.017 per cent; Zr, 0.32 per cent. This steel gave 307 000 lb./in.^{2} tensile strength with 7.5 per cent elongation in 2 inches, and 21.7 per cent, reduction in area in the heat-treated bar. The structure is fine martensite

(*b*) Steel 1197. C, 0.32 per cent; Si, 1.37 per cent; Mn, 0.60 per cent; Ni, 3.05 per cent; Al, 0.02 per cent; Ti, 0.17 per cent; Zr, 0.32 per cent. This steel is of almost identical chemical composition as one shown in (*a*), but gave only 217 000 lb./in.^{2} tensile strength with 3 per cent elongation in 2 inches and 27.5 per cent reduction in area. The carbon is slightly lower and may partly account for the large amount of ferrite shown in the micrograph, but it is more probable that this is, because the specimen was not heated high enough before quenching

air-cooled specimens (see Fig. 8, *e*, *f*), but the steels also show characteristic inclusions. At a magnification of 500 diameters the two cerium steels that were examined were found to contain a large number of gray inclusions, and also some large circular orange inclusions, with interior light-gray markings. The uranium steels contained deep-blue inclusions (see Fig. 9). It seems that cerium and uranium, in a way somewhat similar to manganese (see Fig. 8, *g*), act both as true alloying elements and to produce soundness in the metal. Copper goes into solution, but did not produce a martensitic pattern in the air-cooled specimens, except in the one of high copper content, 1.35 per cent (see Fig. 8, *h*).

Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron (see Fig. 10). The difficulty experienced in rolling the ingots containing boron is due to the fusibility of this eutectic at the temperatures ordinarily used for rolling. In the ingots that broke in the rolls the cracks in the polished specimens were found to follow the eutectic structure observed in the steels as cast, but in other places no traces were visible. Instead hard spherical particles, evidently of a single constituent of the same appearance as iron carbide, were found (see Fig. 11, *a*, *b*). The mechanical working probably breaks up the eutectic, the iron of the eutectic is absorbed by the iron of the matrix, while the iron-boron-carbon compound coalesces into the hard circular particles. These particles no longer form a weak brittle network and may have an appreciable hardening effect on the properties of the steel which may be desirable for the purpose of armor plate. Care must be taken, however, in the final heat treatment that the steel is not heated to too high a temperature before quenching, as the eutectic will then again appear and render the steel unsuitable (see Fig. 11, *d*). In the unetched state both the eutectic and the hard circular particles are pink, they both etch dark with sodium picrate, similar to simple iron carbide, and are not etched by 2 per cent nitric-acid etching, but appear white in contrast to the etched matrix (compare Fig. 11, *a*, *b* with Fig. 11, *c*).

All of the above elements are true alloying additions; they are metallic constituents of the finished steel. The properties they confer upon the steel can not be established from a microscopic examination alone, but must be determined by physical tests. In the light of the considerations indicated above, however, they may all give good results, but more care perhaps must be taken

in the making and treatment of the cerium, uranium, and boron steels than of the others.

(c) SOUNDNESS OF THE STEELS AND STRUCTURES OF THE NORMALIZED AND HEAT-TREATED SPECIMENS

Not all the steels that were made up were examined under the microscope. Typical specimens, however, were chosen from every class of chemical composition, and all those specimens that gave exceptional or unexpected values in the tension tests were examined. Some samples were examined from the ingot as cast and some from the plates as rolled, but the great majority of the specimens were taken from the tested tension bars.

In most of the steels that contained zirconium and titanium in appreciable amounts there were found in the polished and etched specimens the thin, yellow streaks which are the segregates of the zirconium and titanium inclusions rolled out into plates (see Fig. 12, *a*, steel 1213). Many of the steels also showed small longitudinal cracks in the specimens (see Fig. 12, *a*, steel 1158), while in others there appeared a pronounced dendritic pattern (see Fig. 12, *a*, steel 1215, and Fig. 12, *b*). These features are of sufficient size as to be seen with the naked eye. The streaks and cracks, since they occur longitudinally in the specimens, should not be expected to have much effect in lowering the tensile properties as measured. The dendritic pattern, which of itself is considered undesirable, was not found to be associated particularly with steels that gave low values in tension. In fact, some of the steels which had the highest tensile properties showed a dendritic pattern. This is perhaps because these steels were rolled with the least number of reheatings, giving a better plate by avoiding repeated heatings and oxidation. The steels that were rolled in the latter part of the investigation, presumably most expertly, gave the largest percentage of dendritic structures.

The following is a list of these steels which showed small cracks in the specimens examined (see Fig. 12) and those which had a dendritic structure. The normalized steels are marked N. and the heat-treated ones H. T.:

Cracked:
- 1106, N.
- 1107, N.
- 1109, N.
- 1119, N.
- 1157, H. T.
- 1158, N. and H. T.

Dendritic:
- 1103, N. and H. T.
- 1132, N. and H. T.
- 1135, N.
- 1136, N.
- 1167, N.
- 1168, N. and H. T.

Cracked—Continued
1176, H. T.
1178, N.
1189, H. T
1211, H. T.
1213, N.
1228, N. and H. T.
1229, H. T.
1236, N. and H. T.
1237, H. T.
1258, N. and H. T.
1274, N. and H. T.
1275, N.
1278, N. and H. T.
1286, N.

Dendritic—Continued
1190, N.
1200, N.
1205, N.
1206, N.
1207, N. and H. T.
1215, N. and H. T.
1216, N.
1219, N. and H. T.
1224, N.
1227, N. and H. T.
1231, N.
1237, N.
1244, N. and H. T.
1252, N.—Streaky.
1285, N.
1286, N. and H. T.

The normalized, as well as the heat-treated specimens, were partially decarburized uniformly to the depth of 0.005 inch along the gage length of the tension specimen, which makes 0.010 inch of the diameter of the gage length decarburized. The differences in the microstructures of the air-cooled specimens have already been described. In the heat-treated specimens those that gave the best results in the tension tests invariably had a structure of fine martensite. Wherever appreciable amounts of ferrite were found, together with the martensite in the quenched and tempered specimens, the tension values were not so good. In many cases unexpected low results could be traced to the presence of relatively large amounts of ferrite (see Fig. 13). The variations in the drawing temperatures, if there were any, could not be detected in the microstructure.

Altogether, in this part of the examination 160 micrographs of the steels in the cast, rolled, and finally heat-treated conditions were taken. For lack of space they can not be given here, but they were invaluable in helping to interpret the results of the mechanical tests. By means of this survey of the microstructures of the samples those containing flaws were discovered and eliminated, and any irregular results could be explained. The microscopic "check-up" thus served to relieve any doubts concerning single samples and helped to give weight to the general conclusions of the investigation.

3. MECHANICAL PROPERTIES

(a) TENSILE TESTS

Since the rolled material was one-half inch or less in thickness, it was impossible to use the standard form of tensile specimen having a diameter in the reduced section of 0.505 inch. A shoulder type specimen was used, having a diameter of 0.300 inch at the reduced section and a gage length of 2 inches, as shown in Fig. 14. This ratio of gage length to area of specimen gives values of elongation somewhat less than would be obtained with standard size specimens, and this fact should be borne in mind in interpreting the results. The tensile and also the impact specimens

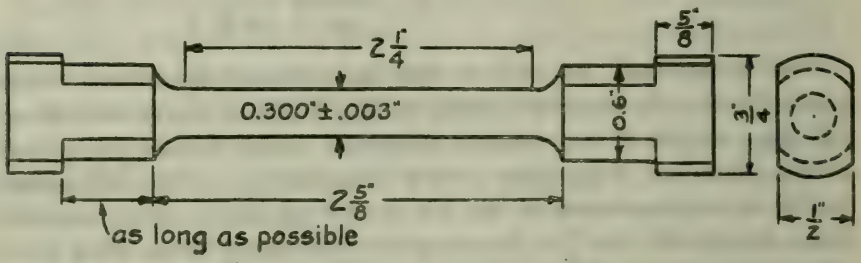


FIG. 14.—*Dimensions of tensile specimens*

were completely machined before heat treatment and not ground before testing.

Tensile tests were made on either a 50 000-pound or 100 000-pound Riehle testing machine. Proportional limit was determined from plotted stress strain curves, strain being measured by means of a Berry strain gage. In a few cases the specimens were too short to admit of fastening a strain gage to the specimen, and blanks appear in the tables (Tables 11–22) for these cases. Yield point was determined by the "drop-of-the-beam" method where any "drop" was observed. Reduction of area and elongation were obtained by the usual measurements after fracture.

Tables 11–22 give the results of the tensile tests on all the steels. It will be noted here that several of the steels have a tensile strength of well above 300 000 lbs./in.^{2}, accompanied by appreciable ductility. No. 1207, with a tensile strength of 344 000 lbs./in.^{2}, was the highest value observed.

TABLE 5.—Hardness Measurements on Plate

[*Indicates specimen not completely broken]

Ingot No.	Thickness	Hardness numerals			
		Brinell		Scleroscope	
	Inch				
1101	3/8	334	293	30	26
	1/2	405	444	52	47
1102	3/8	240	245	27	25
	1/2	217	223	21	22
1103	3/8	207	207	23	23
	1/2	223	212	32	31
1104	3/8	207	194	20	21
	1/2	187	205	20	22
1105	3/8	172	241	28	28
	1/2	232	207	30	28
1106	3/8	189	235	24	25
	1/2	202	216	21	26
1107	3/8	189	182	22	20
	1/2	187	196	20	21
1109	3/8	236	231	24	..
	1/2	244	255	26	..
1111	3/8	317	335	30	..
	1/2	340	351	33	..
1112	3/8	415	302	41	31
	1/2	290	438	39	40
1113	3/8	467	244	39	34
	1/2	477	484	43	43
1114	3/8	537	491	48	49
	1/2	555	520	62	60
1115	3/8	364	354	34	37
	1/2	361	340	47	42
1117	3/8	626	508	43	43
	1/2	600	576	57	68
1118	3/8	626	626	54	54
	1/2	.....	.....	.....	
1119	3/8	387	364	42	40
	1/2	555	600	54	52
1120	3/8	495	470	52	43
	1/2	418	495	47	52
1128	3/8	380	370	35	36
	1/2	467	418	42	45
1129	3/8	444	387	39	42
	1/2	475	460	47	42
1130	3/8	387	370	37	35
	1/2	338	375	37	35
1131	3/8	652	635	.....	
	1/2	575	534	53	63
1132	3/8	558	552	.....	
	1/2	589	626	55	65
1133	3/8	387	488	40	54
	1/2	444	402	45	40
1134	3/8	477	470	42	48
	1/2	444	477	55	58
1135	3/8	444	336	.....	
	1/2	512	444	47	43
1136	3/8	491	479	.....	
	1/2	410	375	37	34
1138	3/8	589	608	.....	
	1/2	578	591	50	56
1144	3/8	578	346	53	26
	1/2	589	555	55	50
1145	3/8	351	245	35	25
	1/2	444	352	41	31
1146	3/8	418	390	32	32
	1/2	478	321	45	28
1147	3/8	487	450	52	60
	1/2	387	477	37	45
1155	3/8	585	555	.....	
	1/2	519	550	51	53
1156	3/8	477	516	43	45
	1/2	537	534	56	55
1157	3/8	418	423	38	39
	1/2	518	522	55	59
1158	3/8	544	640	.....	
	1/2	452	452	50	51
1159	3/8	294	327	32	32
	1/2	603	477	55	45
1160	3/8	573	279	.....	
	1/2	556	545	60	52
1161	3/8	285	440	24	42
	1/2	432	512	31	47
1162	3/8	321	337	24	23
	1/2	387	338	38	37
1163	.....	219	234	21	22
1164	.....	375	340	30	28
1165*	.....	338	346	36	40
1166	.....	430	514	.....	
1167	.....	364	387	33	32
1168	.....	421	385	44	43
1169	.....	640	571	.....	
1170	.....	550	600	61	57
1171	.....	387	447	34	41
1172	.....	424	428	43	37
1173	.....	328	302	28	26
1174	.....	226	206	19	19
1175*	.....	472	467	52	52
1176	.....	470	481	36	38
1177*	.....	477	477	55	55
1180	.....	196	211	19	23
1181	.....	208	216	20	21
1182	.....	213	224	20	21
1183	.....	257	241	.....	
1184	.....	171	172	18	19
1185	.....	211	244	.....	
1186	.....	381	403	.....	
1187	.....	300	311	.....	
1188	.....	342	336	.....	
1189*	.....	351	360	42	44
1190	.....	351	325	34	29
1191	.....	344	338	29	28
1192	.....	228	217	24	23
1193	.....	252	233	26	26
1194	.....	439	457	52	53
1195	.....	444	403	42	38
1196	.....	465	398	46	34
1197	.....	415	369	36	36
1198	.....	209	218	23	24
1199	.....	216	210	24	23
1200	.....	321	302	37	28
1201	.....	268	266	26	26
1202	.....	207	199	21	21
1204*	.....	477	457	50	53
1205	.....	505	512	41	45
1206	.....	481	491	42	47
1207	.....	627	600	55	55
1208	.....	629	616	69	61
1209	.....	600	555	66	62
1210	.....	378	411	38	44
1211	.....	456	447	46	40
1212*	.....	367	361	43	45
1213	.....	471	564	42	51
1214	.....	481	495	41	37
1215	.....	600	553	53	48
1216	.....	418	387	34	35
1217	.....	475	477	55	55
1218	.....	310	278	30	28
1219	.....	235	228	23	23
1220	.....	441	337	45	36
1221	.....	312	323	33	33

TABLE 5.—Hardness Measurements on Plate—Continued

[*Indicates specimen not completely broken]

Ingot No.	Thickness	Hardness numerals		Ingot No.	Thickness	Hardness numerals	
		Brinell	Scleroscope			Brinell	Scleroscope
	Inch				Inch		
1222*		366 367	47 49	1259		596 605	47 48
1223		357 317	33 26	1260		532 569	57 48
1224		406 438	32 34	1261		207 223	18 19
1225		467 387	32 41	1263		402 373	37 40
1226		430 454	36 37	1264		387 396	43 43
1227		550 537	54 54	1267*		180 183	27 25
1228		629 627	66 62	1268		252 219	23 22
1229		585 573	57 55	1269*		207 188	
1230		603 605	70 69	1270*		351 364	20 21
1231		520 474	47 42	1271*		341 342	38 40
1232		494 505	44 46	1272*		250 321	25 30
1233		321 311	28 26	1273*		255 216	32 24
1234		364 375	30 30	1274*		444 418	52 43
1235		351 241	23 22	1275*		555 600	55 60
1236		484 472	54 53	1276*		534 570	52 54
1237		600 585	56 54	1277*		410 444	42 51
1238		444 474	46 49	1278*		395 397	44 43
1239		532 555	59 61	1279*		490 520	50 60
1240		509 516	41 42	1280*		510 486	60 57
1241		520 512	47 47	1281*		508 468	60 59
1242		387 430	39 41	1282*		510 475	57 53
1243		460 438	42 43	1283*		539 512	57 58
1244		441 420	44 45	1285*		475 430	49 47
1245*		525 493	56 57	1286*		520 508	54 52
1246		444 444	39 36				
				1289*		340 447	38 49
1247		366 418	33 36	1290*		455 498	51 55
1248		248 256	20 20	1291*		464 478	50 49
1249		361 371	19 18	1292*		522 486	60 60
1250		324 324	28 26	1293*		418 470	39 47
1251		477 495	39 37				
1252		477 487	40 39				
1253		600 560	53 49				
1256		532 495	49 49				
1257		524 477	52 47				
1258		441 440	38 40				

(b) IMPACT TESTS

Impact tests were made on heat-treated specimens from all heats beyond No. 1155 and a few previous, the heat treatment being the same as for the tensile specimens and plates. Hardness tests made on a few impact specimens gave sufficient evidence that the impact specimens were in a structural condition similar to the tensile specimens. An Izod machine using a cantilever type of specimen was used in all impact tests.

Here, again, the thickness of the available material precluded the use of the standard type of specimen in all cases. For those plates which would not admit of making a round specimen 0.450-inch diameter (see Fig. 15), the largest diameter possible in multiples of 0.050 inch, was used and the notch made geometrically similar to the larger specimens. The total length of the specimens re-

mained constant, so as not to alter the striking distance. The specimens of small size were held in the anvil of the impact machine by means of hardened steel split sleeves having an outside diameter of 0.450 inch and an inside diameter to fit the specimen. This sleeve was inserted in the anvil flush with its top surface and the impact specimens properly aligned by means of a templet. The height of fall of the pendulum was varied proportionally to the size of the specimen, although theoretically this should not be necessary.

The area of the specimens at the notch was computed and the energy absorbed in breaking for unit area determined, a value which has been called the specific impact work. The results of the tests are given in Table 6. While the law of similarity has not been definitely shown to hold for impact specimens as for other

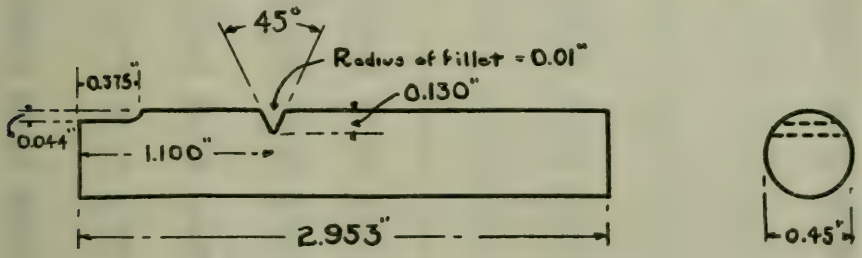


FIG. 15.—*Dimensions of impact specimens*

forms of mechanical testing, the method used was considered the most desirable that the circumstances would permit.

A high impact value does not always indicate a superior steel, since such values are many times accompanied by low tensile strength. Thus, all the steels which had an impact value greater than 200 foot-pounds per square inch also gave tensile strengths less than about 130 000 lbs./in.^{2}, except No. 1252, which had a tensile strength of 324 800 lbs./in.^{2}. On the other hand, if we select all those steels which showed an impact value less than 50 we note that the majority of that group have a tensile strength in excess of 275 000 lbs./in.^{2}, although a few fall even below 100 000 lbs./in.^{2}, the latter being clearly inferior steels. Those steels, then, that show fair values of impact, together with high tensile strength, should be considered the best steels, since they combine strength with toughness.

TABLE 6.—Impact Tests (Izod Machine)

[*Indicates specimen not completely broken]

Ingot No.	Diameter of specimen	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
1135	0.450	0.1210	120	7.0	58
1136	.450	.1210	120	8.0	66
1138	.447	.1196	120	6.5	54
1155	.447	.1196	120	13.5	113
1156	.447	.1196	120	5.0	42
1157	.450	.1210	120	13.5	112
1158	.448	.1201	120	5.5	46
1162	.445	.1187	120	6.0	51
1163	.448	.1201	120	29.5	246
1164	.347	.0732	75	8.0	109
1165	.449	.1206	120	9.5	79
1166	.346	.0730	75	8.0	110
1167	.350	.0736	75	4.5	61
1168	.450	.1210	120	12.0	99
1169	.347	.0732	75	5.5	75
1170	.351	.0738	75	4.5	61
1171	.454	.1229	120	16.5	134
1172	.354	.0742	75	11.0	148
1173	.353	.0741	75	9.0	121
1174	.449	.1206	120	16.0	133
1175	.447	.1196	120	10.5	88
1176	.354	.0742	75	8.0	108
1177					
1178	.450	.1210	120	9.5	78
1180	.450	.1210	120	14.0	116
1181	.296	.0524	60	6.5	124
1182	.445	.1187	120	15.0	126
1183	.349	.0735	75	6.0	82
1184	.444	.1182	120	28.0	237
1185	.446	.1192	120	42.0	357
1186	.441	.1168	120	19.0	163
1187	.349	.0735	75	9.0	122
1188	.348	.0733	75	10.0	136
1189	.350	.0736	75	8.0	109
1190	.450	.1210	120	14.5	120
1191	.354	.0742	75	7.5	101
1192	.450	.1210	120	24.5	202
1193	.354	.0742	75	17.5	236
1194	.447	.1196	120	10.5	88
1195	.349	.0735	75	7.5	102
1196	.347	.0732	75	9.5	130
1197	.348	.0733	75	8.5	116
1198	.449	.1206	120	75.5	*625
1199	.345	.0729	75	33.5	*460
1200	.447	.1196	120	14.5	121
1201	.349	.0735	75	16.0	218
1202	.452	.1220	120	41.5	340
1204	.449	.1206	120	12.0	100
1205	.350	.0736	75	7.0	95
1206	.349	.0735	75	9.5	129
1207	.350	.0736	75	5.5	75
1208	.446	.1192	120	4.5	38
1209	.350	.0736	75	1.5	20
1210	.446	.1192	120	14.0	117
1211	.348	.0733	75	9.5	130
1212	.447	.1196	120	12.0	100
1213	.447	.1196	120	4.5	38
1214	.349	.0735	75	6.5	88
1215	.447	.1196	120	6.0	50
1216	.448	.1201	120	13.5	112
1217	.350	.0736	75	6.5	88
1218	.349	.0735	75	9.0	122
1219	.448	.1201	120	17.5	146
1220	.447	.1196	120	9.0	75
1221	.353	.0741	75	9.0	121

TABLE 6.—Impact Tests (Izod Machine)—Continued

[*Indicates specimen not completely broken]

Ingot No.	Diameter of specimen	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
1222	0.450	0.1210	120	11.0	91
1223	.449	.1206	120	9.5	79
1224	.353	.0741	75	7.5	101
1225	.349	.0735	75	8.5	116
1226	.298	.0534	60	4.5	84
1227	.299	.0539	60	4.0	74
1228	.299	.0539	60	2.0	37
1229	.348	.0733	75	8.0	109
1230	.296	.0524	60	.5	10
1231	.350	.0736	75	8.0	109
1232	.299	.0539	60	4.0	74
1233	.300	.0544	60	4.0	74
1234	.349	.0735	75	6.5	88
1235	.350	.0736	75	13.5	183
1236	.349	.0735	75	8.5	116
1237	.351	.0738	75	4.5	61
1238	.298	.0534	60	4.5	84
1239	.299	.0539	60	1.0	19
1240	.299	.0539	60	6.5	120
1241	.298	.0534	60	1.5	28
1242	.351	.0738	75	6.5	88
1243	.300	.0544	60	7.5	138
1244	.349	.0735	75	7.5	102
1245	.299	.0539	60	3.5	65
1246	.300	.0544	60	2.5	46
1247	.350	.0736	75	4.0	54
1248	.351	.0738	75	6.0	81
1249	.349	.0735	75	10.0	136
1250	.299	.0539	60	5.5	102
1251	.299	.0539	60	2.0	37
1252	.298	.0534	60	13.5	252
1253	.298	.0534	60	2.5	47
1256	.450	.1210	120	21.5	174
1257	.400	.0833	100	6.0	72
1258	.250	.0736	75	5.0	68
1259	.399	.0827	100	8.0	97
1260	.400	.0833	100	6.0	72
1261	.449	.1206	120	5.8	48
1263	.400	.0833	100	4.0	48
1264	.450	.1210	120	5.5	46
1267	.398	.0821	100	3.0	37
1268	.400	.0833	100	6.0	72
1269	.449	.1206	120	14.5	120
1270	.398	.0821	100	10.5	128
1271	.449	.1206	120	10.5	91
1272	.397	.0815	100	10.5	128
1273	.397	.0815	100	31.0	380
1274	.389	.0827	100	3.0	36
1275	.450	.1210	120	5.0	41
1276	.450	.1210	120	4.2	35
1277	.348	.0733	75	8.0	109
1278	.450	.1210	120	19.5	161
1279	.448	.1201	120	4.0	34
1280	.448	.1201	120	6.0	50
1281	.449	.1206	120	4.0	33
1282	.450	.1210	120	7.0	58
1283	.449	.1206	120	3.0	25
1285	.449	.1206	120	10.0	83
1286	.449	.1206	120	8.0	66
1289	.349	.0735	75	7.0	95
1290	.350	.0736	75	6.0	82
1291	.349	.0735	75	5.5	75
1292	.350	.0736	75	5.5	75
1293	.349	.0735	75	7.0	95

(c) HARDNESS TESTS

Hardness tests were made on the tensile specimens and on the hardened plates. For the tensile specimens this consisted of two Brinell impressions on the ends of the broken specimens after grinding off the outside surface. Scleroscope hardness was also determined on the same material, several readings being taken with a recording scleroscope.

On the plates opposite corners were ground down and duplicate Brinell and several scleroscope determinations made at each posi-

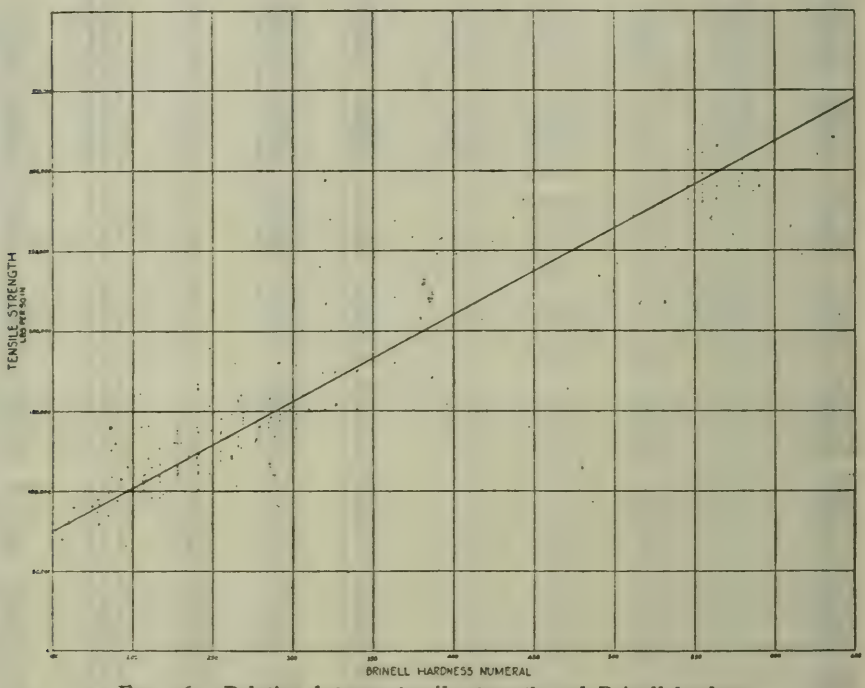


FIG. 16.—*Relation between tensile strength and Brinell hardness*

tion. In this case an indicating scleroscope was used for some of the work and a recording instrument for the remainder. The indicating instrument gave uniformly lower values than the recording type, so that the scleroscope values for the plates are not in all cases intercomparable. Those taken with the latter instrument are marked with an asterisk in Table 5, which gives the hardness values for both corners of each plate.

The method of heat treatment described in Section III–2 does not give exactly the same hardness to both the small tensile specimens and the relatively larger plates. To secure the same hardness, it would have been necessary to draw back the tensile specimens at varying temperatures until like conditions were reached.

By aid of Fig. 16, showing the relation between tensile strength and hardness for this class of steels, an idea of the actual tensile properties of the hardened plates may be obtained.

V. COMPARISON TESTS ON SIMILAR MATERIAL

In addition to the ingots prepared by the Bureau of Mines there was also available for study other material of a similar nature which was submitted through the Bureau of Ordnance of the Navy Department and was secured from one of the large automobile manufacturers who was constructing armored tanks during the war and whose representatives had made great claims for zirconium as an alloying element in light armor plate. This material consisted of 45 plates of ¼ to ½ inch thickness, representing 28 separate heats of steel. Each heat, comprising about 1000 pounds of metal, was made in an electric furnace.

The majority of the plates as submitted were 18 inches square. The following, however, were 12 inches square: 16–1, 19–1, 20–3, 22–2, 22–3, 22–4, 24–5, 25–1, 25–2, 25–4, 25–8, 27–3, and 27–4. (The first number in all cases refer to the heat number and the second to the plate number of that heat.) The plates were supposedly heat treated, but many were found to be soft and were heat treated at the Bureau of Standards in accordance with a summary of the heat treatments given the same material by the manufacturer.

All plates were cut up, the hardened ones by grinding, so as to produce two tensile bars, an impact specimen, and a 12 by 12 inch ballistic plate from the large size plates. From the smaller plates a ballistic plate of 11 by 11 inches was obtained in most cases.

In Table 7 is given the heat treatment of the plates and test pieces on those plates which were heat treated at the Bureau of Standards.

The same type of specimen and testing procedure was used for these materials as for those described above, with the exception that the B and C specimens are both hardened and no tests were made on normalized material.

In Table 12 will be found the results of impact tests calculated in a similar manner to those given before.

A comparison of these tests made at the Bureau and those made by the manufacturer is given in Table 9, the average value for each heat being given. In the grand average certain of the heats are omitted, as noted in the table, since the figures from both sources are not strictly comparable.

TABLE 7.—Comparison Steels

[AC=Air cooled; FC=furnace cooled. All specimens drawn for one hour in oil bath unless otherwise stated]

Heat No.	Temperatures			Remarks	Heat No.	Temperatures			Remarks
	Normalizing	Quenching	Drawing			Normalizing	Quenching	Drawing	
	°C	°C	°C			°C	°C	°C	
2	870 AC	850	205		18	870 FC	850	190	
4	870 AC	850	205		19	816 AC	860	190	
6	870 FC	850	205		20	954 AC	850	316	Salt bath for drawing
8	870 FC	850	193						
9	870 AC	830	193		21	870 FC	850	190	
					22	870 FC	850	190	Drawn for three hours
10	870 AC	830	193						
11	870 FC	777	177		23	870 FC	827	205	
12	870 AC	843	205		24	870 AC	860	205	
13	870 FC	850	205						
14	870 FC	843	288	Salt bath for drawing.	25	900 FC	850	205	
					26	800 AC	800	200	
					27	816 AC	843	204	
15	870 FC	827	290	Do.	28[a]	800 AC	800	200	
16	870 FC	830	193						

[a] These values not given by manufacturer, but estimated at Bureau of Standards.

Table 10 gives the results of hardness measurements on ground portions of opposite corners of the plates. The results that were obtained on these comparison steels are quite similar to those obtained on our own material, but it will be noted that the highest tensile properties observed were not so great as those from the regular series. The comparison steels will therefore be included in the discussion of results and the effect of the various elements on the properties of steel.

TABLE 8.—Impact Tests (Izod Machine) of Comparison Steels

Steel	Diameter of spec.	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
2-1	0.449	0.1206	120	17.0	141
4-1	.397	.0815	100	6.0	74
6-1	.448	.1201	120	4.0	34
8-1	.399	.0827	100	12.0	145
9-1	.449	.1206	120	4.0	33
9-2	.400	.0833	100	3.5	42
10-2	.450	.1210	120	14.0	116
11-2	.400	.0833	100	14.0	168
12-1	.399	.0827	100	13.0	157
13-2	.499	.1206	120	6.0	50
14-1	.399	.0827	100	15.0	181
15-1	.400	.0833	100	6.0	72
16-1	.349	.0735	75	3.0	41
18-1	.450	.1210	120	15.0	124
19-1	.349	.0735	75	7.0	95
20-1	.348	.0733	75	5.5	75
20-3	.449	.1206	120	6.0	50
22-1	.349	.0735	75	8.0	109
22-2	.450	.1210	120	16.5	136
22-3	.449	.1206	120	9.0	75
22-4	.449	.1206	120	9.0	75
23-1	.349	.0735	75	9.0	123
24-5	.348	.0733	75	7.0	96
25-1	.398	.0821	100	11.0	134
25-2	.449	.1206	120	9.0	75
25-4	.398	.0821	100	10.5	128
26-1	.349	.0735	75	2.0	27
27-3	.301	.0549	60	4.0	73
27-4	.349	.0735	75	8.0	109
28-1	.450	.1210	120	4.0	33

TABLE 9.—Comparison Steels

[Comparison of Bureau of Standards and manufacturers' tests]

Kind of steel	Heat No.	Bureau of Standards' tests					Manufacturers' tests				
		Tensile strength	Yield point	Elongation in 2 inches	Reduction in area	Brinell hardness numeral	Tensile strength	Elastic limit	Elongation in 2 inches	Reduction of area	Brinell hardness numeral
		Lbs./in.²	Lbs./in.²	Per cent	Per cent		Lbs./in.²	Lbs./in.²	Per cent	Per cent	
Ni, Si, Zr	1	257 100	188 800	11.3	37.3	523	301 000	250 000	10.5	25.9	555
Ni, Si, Zr	2	228 800	202 900	9.6	35.3	436	272 000	231 000	10.5	31.5	477
Ni, Si, Zr, Co, Mo	3	288 600	229 500	7.8	26.2	589	304 000	264 500	11.8	33.8	567
Cr, V, Mo	4	253 200	238 500	.3	1.0	556	202 000	202 000	1.0	3.3	532
Ni, Si, Cr, Zr	5	308 800	247 900	8.8	20.1	615	285 000	263 000	2.0	6.4	555
Cr, V, Mo	[a] 6	237 200	209 900	2.3	4.1	540	[b]	[b]			600
Ni, Si, Zr	7	282.500	254 700	8.5	18.3	584	294 000	264 000	6.5	8.8	555
Ni, Si, Zr	8	245 000	202 800	8.6	29.0	440	265 000	210 000	16.5	16.5	512
Cr, V, Mo	9	186 500		5.1	.6	556	183 000		1.0	1.0	566
Ni, Si, Zr	10	285 600	259 400	7.8	31.5		225 000	200 000	10.0	36.0	532
Ni, Mo, Zr	11	208 700	187 800	7.8	28.6	324	202 500	176 500	13.5	46.5	444
Ni, Si, Cr, Zr	12	283 300	221 600	9.1	33.3	445	295 500	255 000	4.5	9.0	555
Ni, Si	[a] 13	172 700	[c]	[c]		545	284 000	250 000	10.0	30.0	578
Ni, Co, Si, Zr	14	325 400	268 300	8.5	19.8	534	281 000	238 000	10.3	32.0	545
Ni, Si, Co, Mo	[a] 15	226 700	[c]	[c]		509	260 000		1.0	5.0	578
Ni, Si, Zr	[a] 16	236 800	226 200	1.0	4.7	564	[b]	[b]			512
Ni, Si, Zr	[a] 17	[d]	[d]	[d]	[d]		272 500	233 500	8.5	27.0	477
Ni, Si, Zr	18	253 900	208 800	11.5	32.9	555	285 700	250 000	10.7	30.7	543
Ni, Cr, Si, Zr	19	262 600	227 800	1.5	3.3	567	287 000	250 000	3.0	5.0	555
Ni, Si, Zr	20	301 800	236 900	5.7	14.9	542	312 000	254 500	10.3	30.0	534
Ni, Si, Zr	21	252 500	245 800	10.0	28.4	424	270 000	235 000	12.5	44.0	512
Ni, Co, Si, Zr	22	277 900	238 100	8.7	38.4	512	290 000	245 000	11.0	43.0	512
Ni, Si, V	23	292 300	224 600	.1	3.4	512	326 000	270 000	7.8	16.0	534
Ni, Si, Zr	24	281 500	228 800	9.0	33.4	578	297 000	242 000	8.5	21.5	532
Ni, Si, Zr	25	303 600	245 100	9.5	30.7	600	309 000	245 000	10.5	29.0	544
Ni, Si, Zr	[a] 26	[c]	[c]			636	[e]	[e]			
Ni, Si, Zr	27	283 800	254 200	7.9	31.9	385	295 000	250 000	2.5	4.5	600
Ni, Si	[a] 28	[c]	[c]			593	[e]	[e]			
Average		269 700	230 600	7.5	23.5	514	275 300	239 800	8.3	22.6	536

[a] Values for these heats not included in average. [b] Broke in head. [c] Broke in shoulder. [d] Not tested in heat-treated condition. [e] No values given

TABLE 10.—Comparison Steels

[Hardness of plates on opposite corners]

Plate No.	Hardness numeral				Plate No.	Hardness numeral			
	Brinell		Sclero-scope			Brinell		Sclero-scope	
1–3	532	495	61	[a] 60	17–1	262	262	29	[a] 30
2–1	418	402	49	47	18–1	512	526	60	62
2–2	375	387	44	[a] 45					
3–1	607	532	62	[a] 61	18–2	273	277	32	[a] 5
4–1	510	495	53	51	19–1	486	522	58	
					19–2	293	293	32	[a] 33
4–2	311	311	38	[a] 38	20–1	504	516	56	57
5–1	600	546	57	[a] 55	20–3	514	571	57	66
5–2	600	600	65	[a] 65					
6–1	555	578	63	67	21–1	474	470	58	56
6–2	477	495	55	[a] 57	22–1	514	479	61	58
					22–2	553	512	67	55
7–1	600	555	58	[a] 55	22–3	495	474	58	47
7–2	512	495	62	[a] 60	22–4	474	465	47	44
8–1	474	452	53	52					
9–1	560	555	66	65	23–1	571	544	72	68
9–2	555	568	61	63	24–5	532	483	64	58
					25–1	522	518	56	55
10–2	508	512	57	63	25–2	529	553	59	61
11–2	418	418	56	53	25–4	510	526	57	61
12–1	509	512	65	67					
13–1	258	262	33	[a] 35	25–8	544	550	65	67
13–2	567	522	66	64	26–1	562	562	71	69
					27–3	407	446	47	48
14–1	504	500	66	59	27–4	439	452	53	54
15–1	512	486	60	59	28–1	522	480	60	54
16–1	477	460	50	49					

[a] Plates not heat treated at Bureau.

VI. EFFECT OF VARIOUS ADDITION ELEMENTS

The large number of steels examined offers an excellent opportunity for studying the effects of the various alloying elements. In nearly all the heats, however, the silicon content is higher than that usually obtained in ordinary practice. For purposes of comparison it is necessary to classify the steels into groups having the least possible number of variables in each group. The carbon content is a variable in practically every group, and the arrangement given in the tables is according to increasing carbon content.

The groups into which the steels have been roughly classified are as follows: Group A, silicon steels; Group B, nickel-silicon steels; Group C, silicon-zirconium steels; Group D, nickel-silicon-zirconium steels; Group E, cerium steels; Group F, copper steels; Group G, boron steels; Group H, uranium steels; Group I, molybdenum steels; Group J, nickel-chromium steels; Group K, vanadium steels; Group L, chromium-tungsten steels; Group M, cobalt steels.

1. GROUP A—SILICON STEELS

This group, shown in Table 11, represents plain carbon steels in which the silicon is greater than normal and which have all been deoxidized with aluminum. The group has been further divided into steels that have greater or less than 1 per cent silicon. It will be noted that the increase of silicon to above 1 per cent has resulted in a greater tensile strength and impact value without materially reducing the ductility. Nos. 1269 and 1270, containing, respectively, 0.65 per cent titanium and 0.45 per cent aluminum, show no superiority over No. 1104, which is simply deoxidized with these elements.

2. GROUP B—NICKEL-SILICON STEELS

Table 12 illustrates this group which has been further classified into steels containing 2 per cent nickel, 3 to 3.25 per cent nickel with silicon greater or less than 1 per cent, and those having more than 3.25 per cent nickel.

The class with 2 per cent nickel all contain approximately 1 per cent silicon and show increased mechanical properties in comparison with the corresponding class of Group A. A few steels in this class have tensile strength in the neighborhood of 300 000 lbs./in.^{2}, but the ductility and toughness are not as great as in those that follow.

The 3 per cent nickel group again shows the advantage of increasing the silicon to greater than 1 per cent. In fact, this combination of elements represents about the best of any of those tested, the majority having a tensile strength from 270 000 to 315 000 lbs./in.^{2}, depending upon the carbon content, yield point from 200 000 to 250 000 lbs./in.^{2}, and proportional limit from 100 000 to 160 000 lbs./in.^{2}, excellent ductility and satisfactory impact values. The values for the normalized steels are also excellent. A carbon content of from 0.40 to 0.50 seems to be the most favorable.

The nickel content apparently should be kept in the range 3 to 3.25 per cent, as those steels having a higher percentage than this were nearly all brittle.

Group B also shows, as did Group A, that aluminum and titanium in amounts greater than that needed for deoxidation offer no advantage and, in fact, appear to be in most cases detrimental.

3. GROUP C—SILICON-ZIRCONIUM STEELS

This group as tabulated in Table 13 should be compared with Group A, which contains similar steels without zirconium. The zirconium content is variable from a small amount to 0.60 per cent. A study of Tables 11 and 13 seems to indicate that in the steels of lower carbon content the zirconium may have increased the ductility but not the tensile strength for the heat-treated steels. In the higher carbon range the ductility is much less than for similar steels in which zirconium is absent. The normalized steels containing zirconium have lower proportional limit, yield point, tensile strength, and ductility than those of Group A.

4. GROUP D—NICKEL-SILICON-ZIRCONIUM STEELS

These steels shown in Table 14 are subclassified similar to those of Group B. The 2 per cent nickel steels do not give as great tensile strength with zirconium as without it, but seem to show greater ductility and toughness. The same may be said of the 3 per cent nickel steels, although in this case the ductility is not increased to as great an extent, if any. There are several places in the table where the carbon content is constant and zirconium practically the only variable. None of these instances, however, show any regular effect on the properties attributable to the zirconium content.

5. GROUP E—CERIUM STEELS

The cerium steels without nickel, as shown in Table 15 and compared with the first portion of Group H, indicate that with about 0.25 per cent of cerium the tensile properties are increased with accompanying loss of ductility. The nickel-cerium steels have been arranged partly in order of cerium content in the table, since they are all of approximately the same carbon content. Although nearly all of the nickel-cerium steels have the nickel-silicon ratio shown in Group B to be desirable, it also appears that small amounts (up to 0.10 per cent) of cerium are beneficial, while larger quantities offer no further advantage. No. 1260, with only 0.01 per cent cerium, is a most excellent steel.

The rôle of cerium is thought to be that of a desulphurizer, and in Nos. 1256 and 1257 the sulphur content was intentionally increased to investigate this point. The tensile strength of these two steels is quite high, but the ductility is less than would be expected from a consideration of the other constituents. In amounts over 0.30 per cent cerium segregates very badly, and accordingly it would appear preferable to keep it below this figure.

6. GROUP F—COPPER STEELS

The copper has been added to these steels in place of a portion of the nickel content, and an inspection of Table 16 indicates that in those steels in which the sum of the nickel and copper, together with the silicon and carbon, are in the favorable ratio the usual high tensile strengths are secured, but with a reduction of the ductility and toughness. Specimens Nos. 1279 and 1280, for instance, broke in the shoulders, while the impact values are mostly low. No. 1285, with 0.70 per cent zirconium, apparently corrected for some of the lost ductility.

7. GROUP G—BORON STEELS

This group can almost be dismissed from further consideration because of manufacturing difficulties in producing sound steel containing boron. The majority of the steels (see Table 17) were of low carbon content, but do not compare favorably with similar steels of Groups H and B. The ductility is in all cases low even with small amounts (0.02 per cent) of boron. No. 1276, containing the favorable ratio of carbon, silicon, and nickel, did not show the high properties for that class.

8. GROUP H—URANIUM STEELS

There were only three steels containing uranium—Nos. 1228, 1229, and 1244—all having the favorable ratio of carbon, silicon, and nickel except No. 1228, which carried 0.63 per cent carbon. No 1244 showed the usual high properties, but the other two were less desirable (see Table 22).

9. GROUP I—MOLYBDENUM STEELS

With the possible exception of Nos. 3, the molybdenum steels (see Table 18) do not show the remarkable ductility claimed elsewhere for this element.[5]

This may, of course, be due to type of heat treatment to which all of these steels were subject, but it is probable that all of the steels in the nickel-molybdenum series would have been superior for the purpose desired with the molybdenum omitted.

[5] Molybdenum as an alloying element in structural steels, G. W. Sargent, Proc. Am. Soc. for Test. Mats. 20, Part II, p. 5; 1920.

10. GROUP J—NICKEL-CHROMIUM STEELS

The nickel-chromium steels classified in Table 19 all show good properties particularly regarding ductility and toughness. Although most of the steels contain zirconium also, the previous considerations would not indicate that this element has greatly influenced the results. The properties of all of the steels in Group J could be reproduced without the addition of either chromium or zirconium.

11. GROUP K—VANADIUM STEELS

This group contains the steel (No. 1207) which showed the highest tensile strength observed in the entire investigation—about 344 000 lbs./in.^{2}. Although the ductility is not so great as in certain of the other steels having very high tensile strength, it is nevertheless considerable for such a steel. In passing it might be worthy of mention that from a portion of the plate from this heat was constructed a spring for a precision aeronautic altimeter. This spring is constantly operating under a computed maximum fiber stress of 100 000 lbs./in.^{2} and shows no elastic hysteresis or aftereffect, which is common to springs in such instruments. The group, as a whole, shows good properties but can not be considered as preferable to Group B (see Table 20).

12. GROUP L—CHROMIUM-TUNGSTEN STEELS

This group, consisting only of Nos. 1177 and 1178, comprises too small a number to permit drawing any conclusions, but apparently offers no particular advantages (see Table 22).

13. GROUP M—COBALT STEELS

The steels in this group (Table 21) are all from the comparison series. All except No. 15, which contained molybdenum in addition, showed high tensile strength, with good ductility and toughness. It is probable that cobalt acts similarly to copper in replacing some of the nickel.

TABLE 11.—Group A—Silicon Steels

LESS THAN 1 PER CENT SILICON

No.	Composition					Normalized							Heat treated							
	C	Si	Mn	Al	Ti	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1269....	0.36	0.55	0.64	0.06	0.65	.....	48 100	81 200	30.0	57.4	160	28	.....	113 000	129 400	10.6	29.1	195	30	120
1270....	.38	.46	.52	.45	.....	43 000	.....	89 600	26.3	50.2	163	24	42 000	.....	111 200	9.5	30.6	.....	28	128
1104....	.39	.66	.58	.01	.03	52 000	61 500	95 400	25.0	46.0	178	27	30 000	56 000	126 000	11.0	26.3	187	26	.....

MORE THAN 1 PER CENT SILICON

1198....	0.24	1.10	0.71	0.01	.....	58 000	61 200	87 300	12.5	59.0	178	28	.....	57 400	99 700	12.5	51.5	185	18	625
1199....	.27	1.10	.75	.01	.....	.....	68 500	94 100	21.5	59.0	196	28	40 000	68 100	105 000	17.0	52.0	207	19	460
1102....	.36	1.15	.65	.03	0.06	40 000	60 400	102 900	23.0	51.5	190	26	40 000	75 000	156 500	8.0	13.1	188	25	.....
1163....	.38	1.40	.81	.01	.....	51 000	64 000	102 000	19.5	53.7	207	21	61 000	.....	145 400	2.0	22.1	255	24	246
1201....	.41	1.25	.74	.02	.....	62 000	69 900	105 300	19.0	48.1	209	28	45 000	85 400	121 900	15.0	53.8	235	31	218
1164....	.42	1.50	.86	.01	.....	79 000	85 900	122 500	20.0	51.5	241	24	137 000	.....	259 400	4.5	15.9	418	59	109
1200....	.60	1.20	.74	.01	.....	65 000	90 800	133 400	15.0	45.1	269	19	105 000	.....	230 600	1.0	4.8	364	33	121

TABLE 12.—Group B—Nickel-Silicon Steels

2 PER CENT NICKEL

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1202....	0.25	0.95	0.61	2.00	0.02	.....	56 000	70 700	94 300	19.0	54.7	191	19	52 000	84 900	127 000	7.0	39.6	255	20	340
1174....	.40	1.23	.90	2.10	.02	0.27	.....	77 600	109 300	21.5	54.4	217	31	56 000	108 400	158 100	7.5	21.1	286	34	133
1165....	.41	1.50	.76	2.05	.01	.....	71 000	91 900	130 200	19.5	50.4	228	36	155 000	.....	294 200	3.5	9.2	321	35	79
1166....	.42	1.35	.80	2.05	Tr.	.....	81 000	88 600	121 400	21.0	54.4	240	32	132 000	.....	261 600	3.0	7.3	418	33	110
1167....	.54	1.25	.75	2.15	.01	.....	49 000	84 800	131 400	17.5	45.2	418	28	170 000	.....	316 700	4.0	16.0	340	30	61
1246....	.56	1.00	.90	2.15	N. D.	.44	.....	.....	115 100	4.0	7.9	286	38	.....	.....	192 800	1.0	.6	600	49	46
1245....	.57	1.85	.94	2.20	Tr.	.....	123 000	125 000	172 500	10.5	20.2	322	50	154 000	262 600	322 700	2.0	2.0	652	74	05
3 TO 3.25 PER CENT NICKEL, LESS THAN 1 PER CENT SILICON																					
1120....	0.44	1.00	0.97	3.15	0.01	.....	35 000	.....	178 500	4.5	4.0	302	30	126 000	.....	286 000	2.5	2.7	537	52	.....
1242....	.45	.65	.81	3.00	.06	0.60	56 000	80 900	136 200	15.0	30.0	255	32	155 000	185 750	275 900	5.5	14.1	512	55	88
28.....	.48	.90	.80	3.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	.....	33
1114....	.49	.52	.65	3.25	.02	.03	67 100	.....	117 200	11.3	18.9	241	35	170 000	.....	286 000	.6	1.1	444	36	.....
1118....	.51	1.00	1.10	3.20	Tr.	.35	.....	.....	.....	.....	.....	.....	.....	63 000	.....	194 500	1.0	2.1	375	28	.....

3 TO 3.25 PER CENT NICKEL, MORE THAN 1 PER CENT SILICON

1171	0.26	1.15	0.78	3.00	0.01	.....	49 000	81 000	137 600	23.0	54.1	228	23	116 000	.....	232 200	6.0	37.2	382	49	134
1168	.35	1.35	.77	3.05	.01	.....	44 000	90 800	122 500	19.0	48.5	444	43	134 000	.....	268 900	6.5	15.4	364	29	99
1129	.36	1.15	.85	3.20	.01	.....	40 000	80 600	137 300	13.1	27.1	241	28	90 000	.....	275 100	8.0	22.9	402	37	.....
1214	.39	1.40	.77	3.10	Tr.	.....	39 000	105 800	127 300	19.0	45.1	268	28	143 000	231 000	282 200	10.0	36.6	564	47	88
1128	.40	1.10	.86	3.20	.01	.....	50 000	82 000	138 500	4.5	20.0	249	31	140 000	.....	276 000	7.5	25.5	488	51	.....
1130	.40	1.20	.90	3.20	.02	0.33	72 500	87 100	166 900	8.0	8.6	241	32	130 000	196 000	272 000	15.0	26.1	512	53	.....
1251	.40	1.25	1.46	3.15	.01	.....	41 000	83 000	191 100	1.5	3.4	450	57	102 000	.....	286 700	1.0	2.0	587	68	37
1238	.40	1.25	1.99	3.00	Tr.	.....	.....	.....	.....	.....	.....	.....	.....	145 000	279 300	292 700	9.5	31.3	578	46	84
1204	.40	1.45	.86	3.00	.02	Tr.	.....	107 500	141 500	11.0	30.3	269	22	145 000	264 100	292 200	10.5	38.5	502	36	100
1227	.40	1.45	.84	3.10	.01	.....	52 000	97 000	133 800	18.5	52.0	266	41	165 000	204 700	285 900	8.5	38.9	555	52	74
1236	.40	1.45	1.10	3.00	Tr.	.....	.....	145 200	192 700	8 0	9.8	368	44	110 000	255 000	289 700	8.5	35.6	564	45	116
1226	.40	1.60	.90	3.05	Tr.	.....	45 000	96 900	138 900	14.0	42.3	289	35	.....	251 400	282 800	9.5	32.9	555	69	83
1169	.42	1.35	.82	3.10	Tr.	.....	76 000	96 150	136 600	19.5	47.3	255	36	152 000	.....	262 100	1.0	1.6	555	59	75
1147	.43	1.05	.81	3.10	.33	.....	60 000	.....	240 200	4.0	11.5	300	30	136 000	.....	287 400	6.5	22.8	387	32	.....
1216	.43	1.25	.82	3.00	.12	.45	.....	122 200	136 900	17.5	34.4	255	25	.....	205 900	250 800	6.0	14.9	444	33	112
1206	.45	1.25	.81	3.15	.23	.....	45 000	90 000	132 000	20.0	48.4	277	25	.....	267 000	303 000	11.0	34.8	546	44	129
1205	.48	1.35	.71	3.00	.02	.01	65 000	93 600	130 900	17.5	47.3	271	25	150 000	288 600	314 700	5.5	11.1	564	46	95
1215	.49	1.30	.78	3.05	Tr.	.....	53 000	92 300	128 900	21.0	53.3	266	26	145 000	232 500	296 500	7.5	12.9	591	56	50
1237	.49	2.20	.94	3.05	Tr.	.....	72 000	108 000	155 600	14.5	40.9	317	45	.....	258 100	312 600	8.0	24.9	532	46	61
1217	.52	1.10	.80	3.05	.17	.45	50 000	89 000	134 100	15.5	42.9	289	28	160 000	251 100	315 200	7.0	20.3	564	37	88
1170	.52	1.25	.79	3.00	Tr.	.....	71 000	99 000	145 600	16.5	41.3	286	37	.....	.....	.....	.....	.....	.....	.....	61
1208	.53	1.25	.97	3.10	.01	.....	55 000	102 700	148 200	12.5	30.6	302	27	130 000	.....	206 500	.5	2.0	600	53	38
1209	.74	1.20	1.13	3.10	Tr.	.....	49 000	131 300	155 200	5.5	30.2	302	46	.....	.....	.....	.....	.....	627	81	20

3.25 TO 3.50 PER CENT NICKEL

1172	0.24	1.30	0.76	3.30	Tr.	.....	44 000	77 100	112 600	23.5	54.2	228	33	121 000	.....	224 100	8.5	32.6	387	42	148
13	.45	1.65	1.01	3.49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	50
1113	.55	1.15	.76	3.55	0.03	0.03	74 000	90 000	132 400	6.5	11.6	284	43	.....	.....	235 000	.25	.7	509	42	.....
1239	.58	1.50	.96	3.50	Tr.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	19

[a] Broke in shoulder.

TABLE 13.—Group C—Silicon Steels with Zirconium

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1184....	0.23	1.30	0.61	Tr.	0.05	0.25	28 000	45 000	79 300	28.5	60.8	179	24	23 000	62 400	99 140	23.5	55.0	187	22	237
1185....	.26	1.35	.71	Tr.	T .08 / B .05	.50 / .30	50 000	63 500	92 200	28.0	65.9	179	17	36 000	54 800	97 100	20.5	54.7	387	28	352
1180....	.33	1.55	.63	Tr.	.10	.50	32 000	48 000	92 500	22.5	51.5	189	27	35 000	.....	135 600	9.0	30.1	228	27	116
1181....	.34	1.70	.69	Tr.	.07	.60	.....	62 100	100 700	24.5	53.7	207	30	.....	91 900	140 400	12.5	26.8	187	31	124
1183....	.36	1.70	.77	Tr.	.06	.22	43 000	.....	106 800	24.5	53.0	206	17	90 000	.....	192 600	4.0	19.8	286	35	82
1107....	.37	.73	.50	0.02	.03	.20	30 000	50 500	95 000	10.0	22.8	179	27	24 000	.....	99 500	9.5	21.3	196	25	.....
1182....	.42	1.55	.76	Tr.	.03	.03	47 000	76 500	115 400	19.0	52.3	212	29	75 000	128 300	148 800	1.5	32.0	269	31	126
1106....	.42	.44	.55	.13	.01	.15	39 000	53 250	101 000	8.0	20.3	186	25	126 000	206 000	236 000	1.5	4.5	509	54	.....
1103....	.45	.50	.67	.02	.02	.03	42 000	.....	99 000	19.5	39.8	185	27	54 000	.....	164 500	5.0	8.5	241	27	.....
1109....	.47	.85	.78	.15	.02	.11	31 000	.....	110 800	16.0	22.7	207	31	50 000	.....	147 500	.5	2.2	292	28	.....
1101....	.51	1.15	.80	.09	.04	.10	53 000	.....	115 400	16.0	38.6	228	29	80 000	.....	262 000	1.5	2.0	520	44	.....
1105....	.56	.54	.75	.07	.02	.09	50 000	56 000	100 700	11.0	18.7	197	27	.....	.....	202 750	.25	.0	454	43	.....

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium

2 PER CENT NICKEL

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1186..	0.26	1.35	0.74	2.00	Tr	0.06	0.25	35 000	.....	110 000	14.5	44.4	207	25	90 000	.....	206 800	8.5	40.3	418	.....	163
1192..	.26	1.50	.76	2.05	Tr	.15	T. 80 B. 35	30 000	62 000	95 600	19.5	57.3	212	26	35 000	89 000	125 300	10.0	40.3	255	24	202
1187..	.29	1.40	.67	1.00	Tr	.07	T. 38 B. 27	42 000	68 400	96 200	28.5	56.1	194	31	67 000	148 900	180 500	4.0	39.3	382	47	122
1193..	.29	1.45	.67	2.05	Tr	.20	.30	49 000	77 000	97 900	23.0	54.3	219	28	46 000	.....	133 700	9.0	41.3	241	32	236
1191..	.32	1.40	.77	2.10	Tr	.09	.40	34 000	77 100	106 800	21.5	54.7	226	29	.....	172 800	201 200	2.5	11.7	306	34	101
1190..	.33	1.45	.70	2.15	Tr	.07	.45	.....	77 400	106 100	22.5	49.3	217	25	.....	148 500	180 200	2.0	24.0	364	33	120
1249..	.35	.46	.62	1.75	0.07	.04	.60	61 000	75 500	103 000	22.0	54.7	216	30	39 000	127 300	143 400	16.5	38.2	289	32	136
1248..	.35	2.00	.76	1.60	.14	.04	.55	51 000	87 300	116 600	21.0	50.1	286	36	.....	98 600	175 300	7.0	23.4	340	43	81
1161..	.38	1.20	.75	2.15	.06	.01	.08	73 000	78 600	115 900	21.0	46.0	228	21	123 000	.....	247 500	4.0	32.2	390	44	.....
1176..	.43	1.10	.87	2.00	.17	.11	.13	61 000	86 900	139 600	19.5	44.9	255	31	166 000	.....	293 700	7.0	24.1	477	37	108
27....	.43	1.26	.71	2.16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	146 200	254 200	283 800	7.9	31.9	385	43	91
1175..	.45	1.45	.97	2.10	.12	.15	.10	49 000	.....	127 600	24.5	42.3	266	32	126 000	.....	282 100	5.5	11.7	444	35	88
1162..	.51	1.25	.66	2.10	.06	.01	.10	34 000	70 000	113 200	18.5	32.7	288	21	73 000	184 700	245 600	33.5	10.7	351	37	51

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium—Continued

3 PER CENT NICKEL, LESS THAN 1 PER CENT SILICON

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1222..	0.33	0.23	0.51	3.00	0.04	0.01	0.07	.....	74 200	95 700	22.5	47.3	183	25	137 000	223 800	239 700	8.5	32.4	387	55	91
1212..	.34	.80	.65	3.05	Tr	.04	.40–.20	42 000	65 500	106 000	24.0	41.7	207	30	100 000	212 500	221 500	10.5	35.6	450	56	100
1223..	.36	.30	.57	3.00	.08	.01	.07	60 000	73 600	106 200	20.0	52.2	196	26	136 000	243 600	269 700	8.5	29.5	324	36	79
1233..	.36	.27	.57	3.05	.02	.01	.16	.....	71 400	103 000	21.5	53.4	265	28	.....	207 600	245 300	8.5	31.9	500	57	74
1240..	.37	.65	.70	3.00	.02	.01	.12	.....	92 400	156 900	6.5	23.8	266	.....	137 000	203 300	273 700	8.5	28.9	512	67	120
1224..	.38	.95	.45	3.05	Tr	.10	.20	60 000	83 700	106 800	24.0	50.5	418	20	63 000	146 800	175 000	8.5	14.8	340	26	101
1243..	.40	.95	.85	3.00	.01	.02	.15	38 000	173 000	200 600	6.5	16.0	324	30	146 000	249 100	281 800	10.0	38.3	546	55	138
1213..	.40	.80	.65	3.15	Tr	.04	.33	42 000	73 000	112 300	20.5	40.9	241	22	150 000	209 800	276 500	6.0	20.8	546	41	38
1232..	.42	.20	.48	3.00	.01	Tr	.11	38 000	67 700	100 300	22.0	48.3	199	27	141 000	228 200	256 100	8.5	32.2	550	63	74
1115..	.43	.20	.73	3.15	Tr	Tr	.05	72 000	.....	121 000	16.5	40.2	210	26	62 000	.....	170 000	5.0	11.6	354	32	.....
1231..	.43	.76	.81	3.00	.05	.02	.15	59 000	148 900	188 900	3.0	18.4	269	34	.....	211 600	290 100	9.5	36.7	546	48	109
1119..	.44	.85	.92	3.15	.01	.01	.05	53 000	100 000	198 000	2.5	33.2	321	35	120 000	.....	297 000	7.0	18.5	546	56	.....
1158..	.44	.75	.73	3.10	.16	.03	.21	47 000	138 200	140 200	8.0	23.2	447	25	172 000	.....	287 000	6.0	17.8	387	42	46
1111..	.46	.27	.59	3.15	.03	.01	.03	77 000	82 200	110 500	17.5	37.3	216	30	95 700	.....	271 000	.7	1.2	438	37	.....
26....	.48	.93	.96	3.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	.....	.....	27
24....	.48	.57	.81	3.18	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	150 000	226 800	281 500	9.0	33.4	578	66	96
20....	.54	.95	.72	3.19	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	121 700	236 900	301 800	5.7	14.9	542	67	75
1241..	.61	.67	.75	3.05	.01	.02	.10	46 000	112 100	145 800	10.0	37.7	269	33	.....	260 300	290 300	3.0	2.7	591	79	28
1230..	1.53	.22	.70	3.00	.04	.04	.08	81 000	100 300	151 400	5.0	11.0	298	42	.....	.....	.....	.....	.....	600	73	10

3 PER CENT NICKEL, MORE THAN 1 PER CENT SILICON

1189..	0.27	1.50	0.73	3.15	Tr.	0.04	0.20	44 000	.....	116 100	20.0	44.4	241	33	110 000	216 000	221 600	18.0	26.8	321	24	109
1188..	.27	1.40	.74	3.15	Tr.	.05	.32	57 000	74 300	100 400	24.5	55.3	197	24	80 000	189 600	199 400	10.0	40.9	344	26	136

1235..	.28	1.45	.46	2.95	0.02	.06	.60	38 000	67 700	110 300	27.5	53.0	216	34	53 000	142 000	154 100	7.0	42.1	.....	39	183
1197..	.32	1.50	.60	3.05	.01	.16	.33	52 000	79 000	109 800	22.5	52.8	228	31	85 000	189 200	217 100	3.0	27.5	321	37	116
1195..	.32	1.50	.65	3.00	Tr.	.07	.50	46 000	84 900	111 100	12.0	15.6	248	30	95 000	.....	187 200	2.0	3.9	382	44	102
1196..	.32	1.50	.65	3.05	Tr.	.13	.55	68 000	82 000	109 200	23.5	52.3	223	33	95 000	217 900	229 600	7.5	36.9	382	39	130
1211..	.32	1.10	.96	3.10	Tr.	.07	T .80 B .35	.....	119 000	140 400	9.0	10.5	279	31	138 000	221 000	237 500	8.0	34.3	488	.....	130
1134..	.34	1.30	.93	3.15	.01	.01	.15	25 500	.....	201 500	5.5	66.5	269	33	140 000	.....	281 000	11.0	13.6	555	58	.....
2.....	.34	1.32	.82	2.60	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	111 000	202 900	228 800	9.6	35.3	436	60	141
1219..	.34	1.35	.38	3.10	.02	.15	.70	48 000	64 900	100 400	24.0	55.6	217	22	.....	129 900	152 800	12.0	33.6	248	22	146
1210..	.34	1.10	.57	3.05	Tr.	.06	.55	60 000	78 900	107 900	22.0	44.7	234	37	106 000	218 000	232 200	6.5	36.5	351	27	117
1290..	.35	2.00	.86	3.00	.14	.03	.40	60 000	150 300	172 100	16.5	20.8	307	38	90 000	216 300	232 000	5.5	12.9	420	48	82
1221..	.36	1.00	.61	3.10	.10	.45	.16	44,000	74 000	110 800	24.0	50.6	228	32	62 000	130 200	173 600	10.0	28.2	319	47	121
21.....	.36	1.01	.82	3.14	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	152 500	245 800	252 500	10.0	28.4	424	62	.....
1194..	.36	1.40	.65	3.05	Tr.	.07	.45	.....	83 800	110 700	23.0	52.0	228	33	.....	229 600	246 600	6.0	34.0	375	46	88
1218..	.36	1.10	.38	3.00	.07	.35	T .80 B .30	60 000	82 600	109 000	23.0	50.6	302	28	.....	153 700	179 200	6.0	23.9	532	34	122
1225..	.37	1.15	.56	3.05	.02	.11	.20	.....	82 200	111 300	21.5	53.3	241	33	130 000	230 900	251 700	4.5	30.3	532	45	116
1293..	.37	1.15	.83	3.20	.02	.02	.05	47 000	142 800	159 900	5.5	22.6	268	38	.....	263 400	284 800	8.5	26.5	454	47	95
1144..	.38	1.35	.84	3.10	.01	.02	.31	59 000	.....	220 200	5.0	5.2	386	23	125.000	.....	307 600	7.5	21.7	436	40	.....
1157..	.39	1.20	.75	3.10	.10	.02	.10	26 000	126 400	132 300	20.0	32.7	255	30	130 000	239 000	242 000	10.0	36.9	502	50	112
1131..	.39	1.05	.90	3.15	.01	.02	.12	54 000	.....	259 000	4.0	5.2	375	32	136 000	.....	267 500	1.0	4.5	512	39	.....
1132..	.39	1.10	.90	3.20	.01	.06	.20	50 000	.....	221 000	2.0	4.2	364	44	135 000	.....	290 600	4.0	8.4	555	43	.....
1145..	.41	1.20	.81	3.15	.10	.02	.14	53 000	.....	175 300	8.0	26.0	240	23	150 000	.....	271 800	7.5	31.9	418	29	.....
1.....	.41	1.65	.80	2.91	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	188 800	257 100	11.3	37.3	523	56	.....
1220..	.43	1.05	.70	3.00	.10	.40	.20	48 000	79 400	118 800	19.5	43.8	255	40	70 000	199 200	219 800	2.5	7.9	387	35	75
14.....	.43	1.56	1.08	3.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	175 000	268 300	325 400	8.5	19.8	534	64	181
1289..	.43	1.55	.83	3.02	Tr.	.03	.40	57 000	205 000	207 900	5.0	7.9	275	38	110 000	217 800	261 600	.0	14.1	396	52	95
1234..	.43	1.85	.70	2.95	.04	.08	.55	86 000	104 600	132 100	17.0	43.4	277	38	.....	237 600	259 000	5.0	12.2	555	69	88
1146..	.44	1.05	.84	3.20	.01	Tr.	.05	35 000	.....	207 100	5.5	13.4	384	25	.....	.....	.....	.....	.....	.....	.....	.....
1138..	.45	1.20	.84	3.10	Tr.	.01	.05	.....	93 400	143 300	14.0	32.2	277	33	.....	177 650	300 800	6.0	9.9	.....	.....	54
1112..	.46	1.10	.66	2.95	.09	.03	.08	50 000	84 000	100 600	11.0	27.5	241	34	.....	.....	296 800	3.5	.0	532	55	.....
25.....	.46	1.05	.93	2.74	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	144 100	245 100	303 600	9.5	30.7	600	68	112
1117..	.47	1.00	1.10	3.20	.01	.01	.07	76 000	.....	230 700	1.0	1.4	444	35	150 000	.....	280 200	2.0	4.1	555	47	.....

[a] Broke in shoulder.

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium—Continued

3 PER CENT NICKEL, MORE THAN 1 PER CENT SILCON—Continued

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P.ct.	P. ct.	P.ct.	P. ct.	P.ct.	P.ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1291..	0.47	1.25	1.00	2.90	0.08	0.02	0.22	.....	123 900	155 700	6.5	10.9	266	32	166 000	.....	234 300	0.0	0.7	491	52	75
1292..	.48	1.78	.93	3.15	.01	.04	.06	57 000	106 800	154 800	18.5	24.3	268	35	150 000	.....	286 100	1.5	1.3	402	47	75
1160..	.50	1.20	.89	3.15	.05	.01	.10	44 000	.....	161 400	0.5	.0	364	32	147 000	.....	216 800	.5	2.0	516	50	.....
1159..	.51	1.20	.72	3.00	.04	.01	.25	60 000	.....	195 200	4.0	11.6	255	20	118 000	.....	291 200	3.0	4.0	440	36	.....
1247..	.54	2.45	.85	2.90	.01	.06	T. 85 B. 71	68 000	106 600	154 300	8.0	31.9	321	35	.....	.....	.....	.....	.....	.....	.....	54
MORE THAN 3.25 PER CENT NICKEL AND MORE THAN 1 PER CENT SILICON																						
1250..	0.15	1.55	0.95	3.55	0.01	0 03	T. 65 B. 35	39 000	96 900	133 400	15.5	49.3	286	41	.....	142 000	156 600	8.5	46.3	320	41	102
11....	.19	.47	.36	7.86	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	110 000	187 800	208 700	7.8	28.6	324	50	168
8.....	.37	2.16	1.14	3.64	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	125 800	202 800	245 000	8.6	29.0	440	62	145
17....	.38	1.39	.89	3.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	(a)	(a)	.....	.....	.....	.....
7.....	.39	1.82	.77	3.33	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	98 500	254 700	282 500	8.5	18.3	584	61	.....
1133..	.39	1.65	.75	3.30	.01	.02	T. 70 B. 30	46 500	.....	148 500	12.0	31.9	262	33	136 000	.....	292 000	7.0	14.8	512	55	.....
16....	.39	1.59	.78	3.35	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	130 000	226 200	286 800	1.0	4.7	564	62	41
18....	.41	1.56	1.01	3.40	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	112 500	202 800	253 900	11.5	32.0	555	41	124
10....	.48	1.16	.88	3.45	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	123 000	259 400	285 600	7.8	31.5	.....	.....	116

[a] Not tested in heat-treated condition.

TABLE 15.—Group E—Cerium Steels

WITHOUT NICKEL

No.	Composition					Normalized							Heat treated							
	C	Si	Mn	Ni	Ce	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impac.
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1268	0.39	0.75	0.68	.....	0.20	37 000	56 600	93 600	6.3	5.4	163	17	85 000	.....	128 200	.....	0.7	418	32	72
1272	.40	.27	.69	.....	.35	27 000	71 200	84 700	8.5	31.1	185	25	120 000	.....	188 900	.....	10.0	248	33	128

WITH NICKEL

1260	0.45	1.30	0.71	2.95	0.01	.....	134 300	143 900	15.6	40.8	269	24	.....	206 500	311 100	8.5	37.2	555	52	72
1256	.41	1.70	.73	2.80	.06	60 000	.....	143 400	7.5	37.6	285	39	175 000	244 900	298 000	7.5	7.2	555	58	174
1257	.46	1.55	.98	2.90	.10	54 000	103 200	176 300	9.5	5.4	321	41	184 000	235 000	312 100	4.6	7.3	.....	66	72
1259	.42	.80	1.15	2.95	T. .31 B. .19	53 000	80 000	127 300	21.0	17.8	217	37	65 000	149 000	202 500	8.6	10.4	228	57	97
1252	.44	1.30	.91	3.00	T. .55 B. .35	....	142 600	158 600	5.5	17.3	302	36	83 000	288 900	324 800	5.5	11.0	600	51	252
1258	.39	.25	.90	2.65	T 1.35 B .66	50 000	74 000	109 100	7.6	16.0	187	34	91 000	154 500	177 500	2.5	2.1	.....	.....	68
1253	.74	1.25	.82	2.25	T. .22 B .07	100 000	115 300	171 000	10.5	36.1	359	48	.....	(a)	(a)	.....	.....	.....	.....	47
1281	.51	1.35	1.04	2.90	.03 Cu. 62	70 000	.....	154 300	1.0	.....	396	40	140 000	.....	251 700	1.0	14.1	530	51	33

[a] Broke in shoulder.

TABLE 16.—Group F—Copper Steels

No.	Composition								Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Cu	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
														Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1285	0.35	1.40	0.76	2.55	0.02	Tr.	0.70	0.62	43 000	133 100	152 700	10.0	23.8	286	29	100 000	233 300	248 000	7.5	20.8	402	55	83
1282	.45	1.10	.84	1.90	Tr.	.....	.....	1.35	80 000	128 200	150 800	11.0	27.2	320	37	.....	273 400	313 300	7.5	36.6	546	57	58
1286	.46	1.30	.82	2.55	Tr.	.....	.....	.64	70 000	134 300	143 700	12.0	38.1	292	38	186 000	279 100	327 900	4.5	7.9	555	63	66
1280	.49	1.25	1.03	2.45	.01	.....	.....	.55	55 000	171 800	173 600	6.0	14.8	326	35	150 000	.....	202 200?	.....	.....	550	60	50
1283	.50	1.25	.78	2.60	.01	.....	.....	.36	85 000	131 500	147 500	12.0	44.7	285	38	.....	261 600	297 900	1.0	1.9	578	68	25
1281	.51	1.35	1.04	2.90	.....	.....	.....	.62	70 000	.....	154 300	1.0	.....	396	40	140 000	.....	251 700	1.0	14.1	530	52	33
1279	.58	.23	.90	2.45	.01	.....	.....	.62	71 000	131 500	139 700	11.5	19.7	279	37	140 000	.....	251 700?	.....	.7	642	70	34

TABLE 17.—Group G—Boron Steels

WITHOUT NICKEL

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Ni	Al	B	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1267	0.16	0.24	0.68	.....	0.06	0.39	.....	46 300	69 800	10.7	23.8	156	15	51 000	.....	96 100	3.9	19.1	217	30	37
1261	.21	1.50	.80	.....	.02	.57	54 000	58 000	84 600	11.5	25.6	217	.....	81 000	147 400	150 000	.5	9.8	555	43	48
1274	.45	.33	.69	.....	.03	.06	.....	84 800	100 500	17.0	41.7	187	23	.....	.....	85 400	.1	.7	387	52	36

WITH NICKEL

1278	0.16	1.20	0.84	3.00	0.02	0.09	40 000	.....	110 400	10.5	10.6	220	22	114 000	.....	170 900	0.8	2.7	387	38	161
1263	.18	1.30	.77	3.00	.02	.30	48 000	.....	65 800	14.0	5.4	196	21	112 000	.....	208 300	3.2	2.0	380	.....	48
1264	.19	.41	.67	3.05	Tr.	.50	55 000	65 000	90 700	10.8	20.8	175	.....	113 000	169 700	214 500	4.3	5.9	387	52	46
1277	.26	.36	.58	3.55	.....	.10	53 000	.....	160 900	12.0	46.8	205	24	135 000	205 100	226 700	2.3	7.9	470	60	109
1276	.47	1.25	.67	2.80	.02	.10	70 000	.....	120 600	17.0	31.1	262	35	100 000	244 900	256 300	3.0	7.9	425	55	35
1275	.69	.36	.50	2.90	.01	.08	57 000	132 900	139 900	11.0	22.6	285	34	170 000	.....	323 100	3.0	3.5	600	68	41

TABLE 18.—Group I—Molybdenum Steels

NICKEL-MOLYBDENUM

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Zr	Mo	Co	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.[2]	Lbs./in.[2]	Lbs./in.[2]	P. ct.	P. ct.			Lbs./in.[2]	Lbs./in.[2]	Lbs./in.[2]	P. ct.	P. ct.			Ft.-lbs./in.[2]
11	0.19	0.47	0.36	7.86	0.29	0.54	.....	.....	.....	.....	.....	.....	.....	.....	110 000	187 800	208 700	7.8	28.6	324	50	168
1135	.42	1.45	.83	3.25	.....	.78	.....	66 000	.....	146 000	23.0	25.9	286	35	83 000	.....	300 100	5.5	8.4	444	33	.....
1136	.44	1.80	.84	3.20	.....	.77	.....	37 500	.....	168 700	21.0	20.2	302	37	100 000	.....	257 700	6.5	12.2	393	36	.....
15	.43	1.28	1.09	3.45	.....	.70	0.38	.....	.....	.....	.....	.....	.....	.....	140 000	.....	226 700?	(a)	(a)	509	70	72
3	.44	1.46	.90	3.06	.37	.27	.59	.....	.....	.....	.....	.....	.....	.....	.....	229 500	288 600	7.8	26.2	589	69	.....

CHROME-MOLYBDENUM-VANADIUM

No.	C	Si	Mn	Mo	Cr	V															
9	0.34	0.22	0.87	0.84	1.30	0.28	.....	.....	.....	.....	.....	.....	.....	91 800	.....	186 500	5.1	0.6	556	68	38
4	.36	.14	.65	.22	1.14	.20	.....	.....	.....	.....	.....	.....	.....	127 500	238 500	253 200	.3	1.0	556	53	74
6	.51	.15	.75	1.45	1.08	.16	.....	.....	.....	.....	.....	.....	.....	105 000	209 900	237 200	2.3	4.1	540	71	34

[a] Broke in shoulder.

TABLE 19.—Group J—Nickel-Chromium Steels

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Zr	Cr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1155	0.38	0.16	0.48	3.60	0.07	0.10	1.14	50 000	198 400	201 700	7.0	28.2	444	41	134 000	257 700	258 600	7.5	29.5	532	57	113
12	.39	1.66	.99	3.54	.....	.25	.54	.....	.....	.....	.....	.....	.....	.....	123 500	221 600	283 300	9.1	33.3	445	58	157
5	.40	1.22	.84	3.34	.....	.28	.88	.....	.....	.....	.....	.....	.....	.....	.....	247 900	308 800	8.8	20.1	615	72	.....
1156	.43	.85	.70	3.55	.02	.....	1.13	113 000	.....	198 900	1.5	1.4	512	61	153 000	.....	290 400	6.0	11.5	578	51	42
19	.43	1.50	.95	3.31	.10	.25	.60	.....	.....	.....	.....	.....	.....	.....	140 000	227 800	262 600	1.5	3.3	567	72	95

TABLE 20.—Group K—Vanadium Steels

No.	Composition					Normalized							Heat treated							
	C	Si	Mn	Ni	V	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1273	0.45	0.38	0.46	.....	0.33	71 000	79 300	107 100	22.0	55.2	208	24	85 000	95 400	115 300	11.7	45.3	196	27	380
1173	.38	1.35	.79	3.00	.30	51 000	87 300	145 300	16.0	46.9	255	38	130 000	.....	288 400	9.0	37.6	.....	43	121
23	.56	1.09	1.14	3.06	.21	.....	.....	.....	.....	.....	.....	.....	170 000	224 600	292 300	.1	3.4	512	69	123
1207	.60	1.30	.79	3.15	.32	83 000	103 200	139 000	19.5	48.4	302	26	.....	276 500	343 600	5.0	7.8	627	60	75
1271	.74	.....	.....	.....	.34	60 000	77 500	116 600	7.5	20.8	217	22	110 000	.....	150 900	2.3	31.0	340	40	91

TABLE 21.—Group M—Cobalt Steels

No.	Composition							Normalized						Heat treated							
	C	Si	Mn	Ni	Zr	Mo	Cu.	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Brinell hardness numeral	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
																			Brinell	Scleroscope	
	P. ct.	P ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.		Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
22.....	0.37	0.92	0.69	2.21	0.25	.....	1.10	.....	.....	.....	.....	.....	.....	143 600	238 100	277 900	8.7	38.4	512	60	99
14.....	.43	1.56	1.08	3.01	.34	.....	.37	.....	.....	.....	.....	.....	.....	175 000	268 300	325 400	8.5	19.8	534	64	181
15.....	.43	1.28	1.09	3.45	.....	0.70	.38	.....	.....	.....	.....	.....	.....	140 000	.....	226 700?	(a)	(a)	509	70	72
3.....	.44	1.46	.90	3.06	.37	.27	.59	.....	.....	.....	.....	.....	.....	.....	229 500	288 600	7.8	26.2	589	69	.....

[a] Broke in shoulder.

TABLE 22.—Miscellaneous Steels

CHROMIUM-TUNGSTEN STEELS

No.	Composition								Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Zr	Ti	Other elements	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
														Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.		Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1177..	0.31	0.13	0.41	3.75	0.10	0.01	0.10	Cr—1.95, W—0.90	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1178..	.32	.14	.38	3.50	Tr.	.....	.....	Cr—2.00, W— .90	66 000	170 900	206 500	3.0	10.9	418	50	150 000	205 000	258 100	8.5	11.0	513	65	78
URANIUM STEELS																							
1244..	0.43	1.30	0.90	3.00	0.01	.....	.....	U—0.34	.....	133 500	183 500	6.0	12.9	289	35	150 000	195 000	309 800	10.5	35.2	627	73	102
1229..	.45	1.05	.75	3.00	.0	.....	.....	U— .36	.....	233 700	239 700	3.0	8.5	317	34	145 000	191 900	282 800	2.5	8.7	532	50	109
1228..	.63	1.20	.84	3.00	.0	.....	.....	U— .52	.....	169 100	176 400	.5	2.7	306	37	130 000	.....	299 800	1.0	3.4	622	61	37

VII. SUMMARY AND CONCLUSION

1. About 193 heats of steel, containing in various combinations the principal variable elements of carbon, silicon, nickel, aluminum, titanium, zirconium, cerium, boron, copper, cobalt, uranium, molybdenum, chromium, and tungsten, have been studied.

2. None of the steels presented any difficulties in rolling into plate except those containing boron.

3. The usual mechanical and impact tests were carried out on all of the steels. It is shown that steel containing 0.40 to 50 per cent carbon, 1 to 1.50 per cent silicon, 3 to 3.25 per cent nickel, and 0.60 to 0.80 manganese and deoxidized with a simple deoxidizer such as alumium can be produced having a tensile strength of approximately 300 000 lbs./in.^{2} with excellent ductility and toughness. This type of steel is recommended for structural material.

4. Although the same high properties are obtained in steels of the above composition with the aid of additional elements, it does not appear necessary to resort to such additions of more costly alloying elements.

5. Zirconium, like titanium and aluminum, acts primarily as a scavenger, and when it is not removed as part of the slag remains in the steel in the form of square bright-yellow inclusions not directly visible at magnifications lower than 500×. It is not considered that these inclusions can be very beneficial, and if they are segregated into groups and rolled out into thin platelike streaks they may be detrimental.

6. Of the other elements that are regarded as special alloying additions, chromium, tungsten, vanadium, and molybdenum go into solution and produce a martensitic pattern in the air-cooled specimens. Cerium and uranium act in a similar manner, but also show characteristic inclusions. Copper goes into solution, but a larger amount is required to produce a martensitic pattern in the air-cooled samples than for the others. Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron. This eutectic is fusible at the temperatures ordinarily used in rolling, but at slightly lower temperatures steel containing boron can be rolled successfully. Hot working breaks up the eutectic, and spherical hard particles, similar to iron carbide globules, are formed.

VIII. ACKNOWLEDGMENTS

An investigation covering so many fields of work required the cooperation of many individuals. The authors consider that any merits the investigation may possess are largely due to their collaborators.

The development of the methods of chemical analysis was the contribution of Dr. G. E. F. Lundell, who, assisted by H. B. Knowles and part time by Ensign R. McLane, J. R. Eckman, and Miss E. R. Ward, also made the chemical analyses for the unusual elements. The rolling of the plates was mainly carried out by R. G. Waltenberg, assisted by R. D. France and W. M. Laughton. The last and F. C. Speidel assisted in determining the mechanical properties. Most of the heat treatment was done by H. R. Yerger and the microexaminations entirely by S. Epstein, and H. Scott was responsible for most of the results in thermal analysis.

WASHINGTON, March 30, 1921.

APPENDIX

THE DETERMINATION OF ZIRCONIUM IN STEEL [1]

By G. E. F. Lundell and H. B. Knowles

(a) PRELIMINARY STATEMENT

The method developed at the Bureau of Standards permits the determination of silicon, aluminum, titanium, and zirconium in one portion of the steel and provides for the following possible interfering elements: Tungsten, chromium, uranium, cerium, manganese, phosphorus, vanadium, molybdenum, copper, nickel, and cobalt.

(b) METHOD

Dissolve 5.00 g of the steel in 50 cc of hydrochloric acid (sp. gr. 1.2) with gentle warming and the addition of one cc portion of nitric acid from time to time to insure solution of the zirconium and titanium and also oxidation of the iron.

When solution is complete, evaporate to dryness, take up in 10 cc of hydrochloric acid (sp. gr. 1.2), again evaporate to dryness, and finally bake at a gentle heat in order to decompose nitrates. Cool, take up in 50 cc of 1 : 1 hydrochloric acid, and filter when the iron is completely in solution. Wash the residue with hot 3 per cent hydrochloric acid. Save the filtrate and washings.

Ignite the residue and paper in a platinum crucible, cool, and weigh. Treat with 1 cc of sulfuric acid (1 : 1) and sufficient hydrofluoric acid, fume off in the usual manner, ignite and weigh to obtain silica, and calculate silicon. Fuse the slight residue left after the hydrofluoric acid treatment with a small amount of potassium pyrosulfate, dissolve in 10 to 20 cc of 5 per cent sulfuric acid and add the solution to the acid extract from the ether separation obtained as described below.

Evaporate the filtrate and washings from the silica determination to a sirupy consistency, take up in 40 cc of hydrochloric acid (sp. gr. 1.1) and extract with ether in the usual manner. (The ether extract will contain most of the molybdenum, and this element may be qualitatively tested for in it. If molybdenum is present, it is more conveniently determined in a separate portion of steel.) The acid extract will contain some iron and all of the zirconium, titanium, aluminum, nickel, chromium, etc.

Gently boil off the ether in the acid extract, add the matter recovered from the silica, oxidize ferrous iron with a little nitric acid, dilute to 300 cc, cool, and precipitate with 20 per cent sodium hydroxide solution, adding 10 cc in excess. The sodium, hydroxide solution should be as pure as possible and free from carbonate. Filter and save the filtrate. Dissolve the precipitate in warm dilute 1 : 1 hydrochloric acid, repeat the sodium hydroxide precipitation, filter, and combine the sodium hydroxide filtrates. Dissolve the sodium hydroxide precipitate in warm dilute 1 : 1 hydrochloric acid and reserve the solution for subsequent analysis.

It is advisable to treat as follows the filter or filters used above: Ignite in platinum, fuse with sodium carbonate, digest the cooled melt with hot water, wash the residue, discard the filtrate and washings, dissolve the residue in hot 1 : 1 hydrochloric acid, and add to the main acid solution. This precaution makes certain the recovery of any zirconium held back on the filter as zirconium phosphate insoluble in acid.

[1] J. Ind. and Eng. Chem., 12, p. 562; 1920.

Determination of Aluminum

(*a*) In the absence of chromium and uranium add a few drops of methyl red to the sodium hydroxide filtrate, neutralize with hydrochloric acid, add 4 cc of concentrated hydrochloric acid per 100 cc of solution, boil, make barely alkaline with ammonium hydroxide, continue the boiling for 3 minutes and set the beaker aside for 10 minutes. If no precipitate settles out, the absence of aluminum is assured. If a white precipitate settles out, aluminum is indicated. This precipitate is always contaminated by phosphorus pentoxide and must be purified as follows: Filter without washing, discard the filtrate, and dissolve the precipitate in warm 1:1 hydrochloric acid. Dilute the solution to 50 cc, make alkaline with ammonium hydroxide, neutralize with nitric acid, and add 2 cc in excess. Warm to 50° C, precipitate the phosphoric acid with molybdate reagent in the usual manner, filter, and wash the phosphomolybdate with an ammonium acid sulfate solution. Precipitate the aluminum in the filtrate as directed above, filter without washing, dissolve the precipitate in warm 1:1 hydrochloric acid, reprecipitate, filter, wash slightly with 2 per cent ammonium chloride solution, and ignite in a platinum crucible. The ignited residue is usually contaminated by silica. Therefore a sulfuric acid-hydrofluroic acid treatment, followed by ignition to alumina over the blast lamp, should be performed. (The sodium hydroxide reagent must be tested for substances precipitable by ammonia, and appropriate corrections must be made in the aluminum determination when these are present.)

(*b*) In steels containing chromium proceed as above until the filtrate from the molybdate precipitation is obtained. Then make the solution ammoniacal, oxidize with a little bromine water, make just acid with 1:2 nitric acid; add ammonium hydroxide in slight excess, heat to boiling, filter, dissolve the precipitate in dilute hydrochloric acid, and reprecipitate the aluminum hydroxide as directed above.

(*c*) In steels containing uranium the only modification which is required is the substitution of ammonium carbonate for ammonium hydroxide as the final precipitant of the aluminum hydroxide.

(*d*) In steels containing vanadium, alumina which is obtained by the above procedures from steels containing vanadium is contaminated by this element. When dealing with these steels, proceed as follows: Fuse the weighed residue with pyrosulfate, extract the cooled melt with 5 per cent sulfuric acid, reduce the vanadium in a Jones reductor having ferric alum in the receiver, titrate the reduced solution with standard permanganate, calculate the vanadium as V_2O_5, and subtract from the original weight.

Determination of Zirconium and Titanium

Dilute the hydrochloric acid solution to 250 cc, neutralize with ammonium hydroxide, so as to leave approximately 5 per cent (by volume) of hydrochloric acid, add 2 g of tartaric acid, and treat with hydrogen sulfide until the iron has been reduced. Filter if the sulfide group is indicated. Make the hydrogen sulfide solution ammoniacal and continue the addition of the gas for five minutes. Filter carefully and wash with dilute ammonium sulfide-ammonium chloride solution. Filter through a new filter if the presence of iron sulfide in the filtrate is indicated. Save the filtrate. (The sulfide precipitate consists of ferrous sulfide in addition to the greater part of any nickel, cobalt, and manganese present in steel. It is preferable to determine these in separate portions of the steel.)

Neutralize the ammonium sulfide filtrate with sulfuric acid, add 30 cc in excess, and dilute with water to 300 cc. Digest on the steam bath until sulfur and sulfides have coagulated, filter, wash with 100 cc of 10 per cent sulfuric acid, and cool the filtrate in ice water. Add slowly and with stirring an excess of a cold 6 per cent water solution of cupferron. (The presence of an excess is shown by the appearance of a white cloud, which disappears, instead of a permanent coagulated precipitate.) After 10 minutes filter on paper, using a cone and very gentle suction, and wash the pre-

cipitate thoroughly with cold 10 per cent hydrochloric acid. Carefully ignite in a tared platinum crucible, completing the ignition over a blast lamp or large Meker burner, cool, and weigh the combined zirconinum and titanium oxides. Fuse with potassium pyrosulfate, dissolve in 50 cc of 10 per cent (by volume) sulfuric acid, and determine titanium colorimetrically or volumetrically. Calculate titanium oxide, subtract the weight found from that of the combined oxides, and calculate zirconium.

(c) NOTES ON THIS METHOD

1. Phosphorous pentoxide contaminates the precipitate to so slight an extent that it can be disregarded.

2. Vanadium interferes no matter what its valency. The interference is not quantitative. If present in the steel, proceed as usual through the weighing of the cupferron precipitate. Then fuse thoroughly with sodium carbonate, cool, extract with water, filter, and determine the vanadium in the filtrate by adding sulfuric acid, reducing through a Jones reductor into a solution of ferric alum-phosphoric acid and then titrating with standard permanganate. Vanadium is thus reduced to V_2O_2 and then oxidized to V_2O_5. Calculate V_2O_5 and subtract from the combined oxides. Ignite in the original crucible the matter insoluble in water, fuse with potassium pyrosulfate and proceed as directed for titanium.

3. Tungsten does not interfere, since it is separated from zirconium and titanium by the sodium hydroxide treatment and from aluminum by the ammonium hydroxide precipitation. If tungsten is present in large amount it may be found desirable to fuse the nonvolatile residue from the silicon determination with sodium carbonate, extract with water, filter, dissolve the residue in hot 1:1 hydrochloric acid, and add to the acid extract from the ether separation.

4. Uranium is partially carried down when present in the quadrivalent condition, but not at all in the sexivalent state. If this element is suspected, boil out all hydrogen sulfide before the cupferron precipitation, oxidize with permanganate to a faint pink, cool, and proceed with the cupferron precipitation.

5. Thorium and cerium interfere, but they are not thrown down quantitatively. In case these elements are suspected the peroxidized solution used for the titanium determination must be quantitatively preserved and reduced with a little sulfurous acid. The rare earths are then separated by Hillebrand method,[2] as follows: Precipitate the hydroxides with an excess of potassium hydroxide, decant the liquid, wash with water once or twice by decantation, and then slightly on the filter. Wash the precipitate from the paper into a small platinum dish, treat with hydrofluoric acid, and evaporate nearly to dryness. Take up in 5 cc of 5 per cent (by volume) hydrofluoric acid. If no precipitate is visible, rare earths are absent. If a precipitate is present, collect it on a small filter held by a perforated platinum or rubber cone and wash it with from 5 to 10 cc. of the same acid. Wash the crude rare-earth fluorides into a small platinum dish, burn the paper in platinum, add the ash to the fluorides, and evaporate to dryness with a little sulfuric acid. Dissolve the sulfates in dilute hydrochloric acid, precipitate the rare-earth hydroxides by ammonia, filter, redissolve in hydrochloric acid, evaporate the solution to dryness, and treat the residue with 5 cc of boiling hot 5 per cent oxalic acid. Filter after 15 minutes, collect the oxalates on a small filter, wash with not more than 20 cc of cold 5 per cent oxalic acid, ignite, and weigh as rare-earth oxides which are to be deducted from the weight of the cupferron precipitate.

The above procedure does not give an absolutely quantitative recovery of the rare earths. Experiments indicate a recovery of approximately 85 per cent of the rare earths present in residues containing 100 mg of zirconia, 2 mg of thoria, and 2 mg of ceria. Attempts which were made to omit the preliminary separation of the rare earths, as fluorides, were unsuccessful.

---

[2] U. S. Geol. Survey, Bul. 700, p. 176.

6. Instead of the prescribed treatment for the removal of the bulk of the iron, Johnson's [3] method of fractional precipitation with ammonium hydroxide may be used. When using this method, it is recommended that the 1:1 hydrochloric acid solution of the ammonium hydroxide precipitate should be further treated as given in the Bureau of Standards method beginning with "oxidize * * * and precipitate with a 20 per cent sodium hydroxide solution." In Johnson's procedure silicon must be determined in a separate portion.

7. After considering the method and studying the notes the reader might ask the question, "Why not use ammonium hydroxide instead of cupferron as the final precipitant?" The disadvantages of such a procedure are the following: (*a*) The necessity for destroying the tartaric acid which is in the solution, with attendant danger of contamination by material resulting from the attack on glassware; (*b*) the coprecipitation of phosphorus and also chromium and uranium when they are present.

The advantages of an ammonia precipitation are: (*a*) It is a cheaper reagent; (*b*) the precipitation of cerium would be complete instead of partial.

The following scheme of analysis is now being tested at this Bureau: Zirconium, titanium, aluminum, cerium, chromium, vanadium, etc., are first separated from the bulk of the iron by Johnson's method, and the hydrochloric acid solution of this precipitate is then treated with sodium hydroxide and sodium peroxide as described by Noyes, Bray, and Spear.[4] It is hoped that this treatment will quantitatively precipitate iron, zirconium, titanium, and cerium, leaving such elements as aluminum uranium, vanadium, chromium, tungsten, molybdenum, and phosphorus in solution. Iron, manganese, and the greater part of the copper, nickel, and cobalt are next separated by precipitation with ammonium sulfide in the presence of tartrate, as recommended by Thornton,[5] and zirconium, titanium (and cerium) are finally precipitated by ammonia after destroying the tartaric acid. The ignited and weighed precipitate is then treated for titanium and the rare earths as described in the Bureau method.

(d) CONFIRMATORY EXPERIMENTS

Below is given a summary of the data obtained in the analysis of the Bureau of Standards acid-open-hearth steel No. 20*a* to which definite amounts of standardized solutions were added.

No.	V present G	Cr present G	Cu present G	Ni present G	Al added G	Al found G	T added G	Ti found G	Zr added G	Zr found G
1	0.0005	0.0009	0.0034	0.0009	None	None	None	None	None	None
2	.0005	.0009	.0034	.0009	None	None	None	None	None	None
3	.0005	.0009	.0034	.0009	0.0100	0.0101	0.0100	[a] 0.0102	0.0101	[b] 0.0097
4	.0005	.0009	.0034	.0009	.0100	.0094	.0100	[a] .0102	.0101	[b] .0097
5	.0005	.0009	.0034	.0009	.0500	.0502	.0476	[c] .0482	.0500	[b] .0493
6	.0005	.0009	.0004	.0009	.0500	.0501	.0476	[c] .0482	.0500	[b] .0492

[a] Colorimetrically.

[b] The special treatment for vanadium (see note 2) was not carried out. This furnishes an interesting light on the slightly higher values for titanium obtained both colorimetrically and volumetrically and the correspondingly lower values for zirconium which resulted on account of the omission of this step.

[c] Volumetrically after reduction in a Jones reductor and collection in ferric-alum solution.

[3] Loc. cit.

[4] Technology Quarterly, 21, p. 35, 1908.

[5] Am. J. Sci., 37, p. 173, 1914.

The following modifications of the above method were employed by Lieut. R. McLane in the analysis of zirconium steels at the Ithaca station of the Bureau of Mines:

1. Treat the evaporated solution containing silica with 25 cc of hydrochloric acid (sp. gr. 1.2), again evaporate to dryness, bake and take up in 30 cc of hydrochloric acid (sp. gr. 1.2)+40 cc of water.

2. Ignite the insoluble residue and without weighing (silica being obtained on a separate sample by dehydration with sulphuric acid) add 2 cc of sulphuric acid (sp. gr. 1.84), an excess of hydrofluoric acid, and fume off the sulphuric acid. Dissolve the unignited residue in hydrochloric acid (1 : 1) and add to the acid extract from the ether separation.

3. Evaporate the filtrate from the silica determination to 25–40 cc volume, cool by placing in a larger beaker through which a stream of water is passed, and add 200 cc of ether. Stir, let settle, decant off ether, add 100 cc more ether, and repeat the operation. Perform a third extraction, if necessary, and pipette off the last of the ether, thus avoiding any transfer of the solution.

4. To separate aluminum, heat the oxidized solution to boiling and pour it with constant stirring into 135 cc of hot sodium hydroxide solution (20 per cent) contained in a 600 cc Pyrex beaker. After the precipitate has settled filter, allow the filtrate to stand overnight, and refilter if a precipitate appears. One extraction carried on as above is sufficient.

5. Place the filters and precipitates in the original beaker, add 25 cc of hydrochloric acid (sp. gr. 1.2), dilute to 125 cc, and heat. Filter off the insoluble, wash, ignite, fuse with sodium carbonate, and proceed as in the method.

6. Add methyl red and 8 cc of ammonia (sp. gr. 0.9) to the sodium-hydroxide filtrate, make slightly acid with hydrochloric acid, dilute to 500 cc, heat to boiling, and make just alkaline with ammonia. Let stand warm for one hour, filter, dissolve the precipitate in hydrochloric acid, and dilute the cooled solution to 100 cc volume. Take out exactly 10 cc for a Fe_2O_3 determination by the colorimetric thiocyanate method. Precipitate the remainder of the solution as above and proceed with the molybdate separation as in the method. Finally deduct nine-tenths of the blank (blank has had SiO_2 and Fe_2O_3 deducted and is usually negligible) and divide the weight of Al_2O_3 by 0.9, giving Al_2O_3.

7. Treat the ignited cupferron precipitate with an excess of sulphuric and hydrofluoric acids, evaporate, ignite, and weigh in order to correct for any silica present.

8. Dissolve the weighed precipitate in sulphuric and hydrofluoric acids, evaporate to fumes of sulphuric acid, and make up to definite volume. Determine TiO_2 in one aliquot portion by the colorimetric peroxide method and Fe_2O_3 in another by the colorimetric thiocyanate method and deduct.

The authors desire to express their thanks to Dr. W. F. Hillebrand for valuable suggestions and advice.

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 208

WEIGHING BY SUBSTITUTION

BY

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E. D. GORDON, Associate Physicist
Bureau of Standards

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WEIGHING BY SUBSTITUTION

By C. A. Briggs and E. D. Gordon

ABSTRACT

This paper describes a plan for making substitution weighings, applicable either to equal-arm balances or compound-lever scales, that has been developed in connection with the standardization of large weights at the Bureau of Standards. It has been prepared to meet a demand for an explanation of substitution weighing which has come from practical scale men in the field who have seen the plan in use by the representatives of the Bureau and who desire to adopt it. The description, however, will also be of interest and value to many workers in engineering and other laboratories who have occasion to weigh large objects accurately. A record form and computation sheet is presented which it will be found advantageous to follow.

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1. INTRODUCTION

Substitution weighing is of great importance when it is desired to obtain very accurately the weight of some particular object and when calibrating or adjusting weights in the process of standardizing them. The purpose of the present paper is to set down for reference and application a procedure which can be employed for substitution weighing with great accuracy where either simple equal-arm balances or compound-lever scales are used. The method outlined gives a plan for using the apparatus in such a manner that the maximum precision in the results will be attained. The plan described is one that has been developed chiefly in con-

nection with the standardization of large weights at the Bureau of Standards on compound-lever scales. It is simple in its essential character and can be applied under almost any conditions where an accurate comparison of weights, large or small, has to be made. For convenience the description of the method has been developed in reference to compound-lever scales, but no difficulty should be experienced in applying it directly to equal-arm scales.

The virtue of the method lies in the fact that the multiplication ratio of the arms of the scale does not affect the accuracy obtained. The precision obtainable is determined by the constancy of the multiplication under given conditions of loading and by the sensibility of the device. It is especially efficient for the calibration or adjustment of a large number of weights of the same denomination.

This paper is prepared primarily for the practical scale man in charge of the construction and care of standards and their use in regular and precision work. The more progressive representatives of the workers in this field have shown a persistent desire to adopt for their use the best methods available, but the subject is not adequately covered in physics textbooks, or any other previous record. Secondly, it is expected that this paper will be of assistance to technical and laboratory workers who have occasion to use weighing apparatus for determining the weights of objects or to calibrate weights with special care.

The principles given herein apply in most cases with equal force to equal and unequal arm balances, such as are used in scale shops where it is the custom to make weighings by the method of substitution, though not with the precision here provided for. For instance, it is possible to take a scale of 10 000 pounds' capacity and by substitution accurately weigh and adjust 10 000-pound weights on the platform, and then using the same scale to standardize small weights from 1 to 10 pounds by weighing them on the counterpoise by the method of substitution.

In reference to the general value of the method of weighing by substitution it may be of interest to state that on a compound-lever scale of 10 000 pounds' capacity 10 000-pound weights were weighed and adjusted with an uncertainty of but 0.04 pound, including the errors in all of the steps. The error present in the scale was 3 or 4 pounds for a 10 000-pound load as weighed directly, but on account of the method used this did not enter into the results. It should also be understood that it is possible to use the substitution method with fine balances in precision weighing.

2. GENERAL SCHEME OF WEIGHING BY SUBSTITUTION

The general scheme of weighing by substitution is quite simple. For standardizing weights the standard first is placed on the scale pan or platform designed to receive it and counterpoised by any

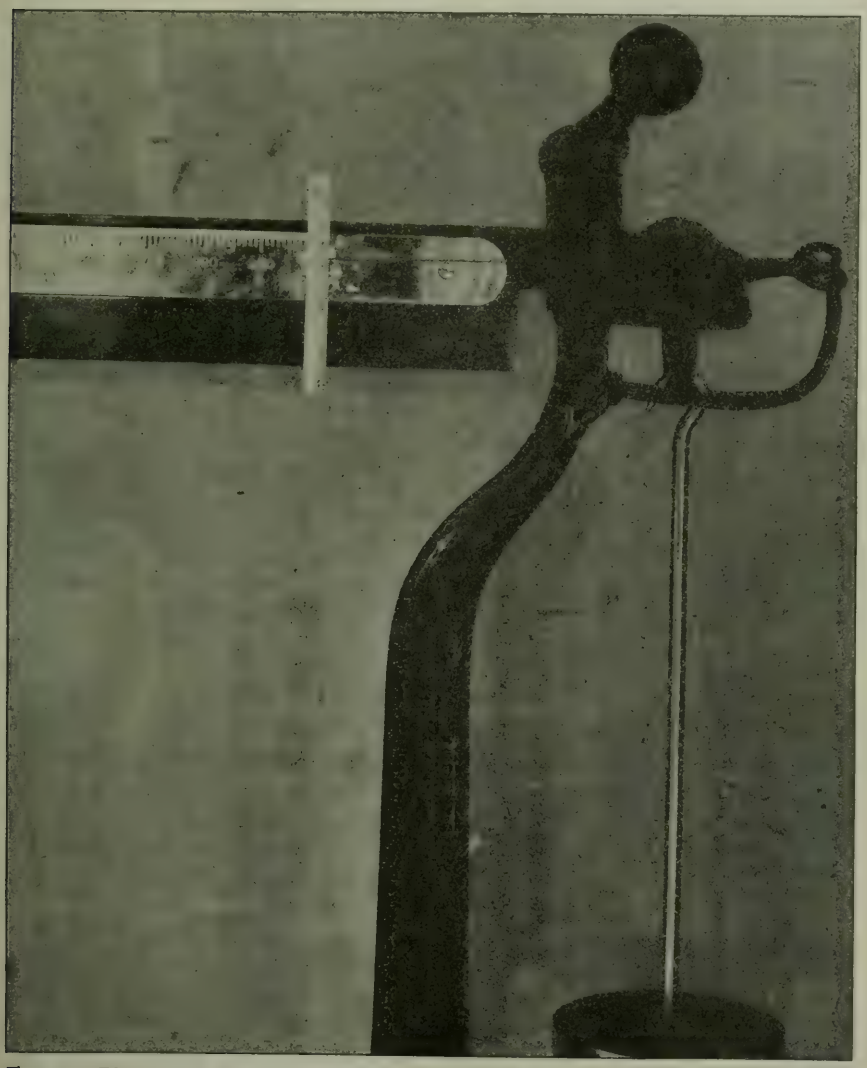

FIG. 1.—*Photograph of scalebeam with graduated millimeter scale mounted upon it and pointer attached to trig loop as for weighing by substitution*

convenient material. When the balance of the beam is obtained, the standard is removed, the weight to be compared is substituted, and the correction is determined from the small weights that have to be added or subtracted to establish the same balance as before.

Where the weight of an object is desired and its weight is not already known approximately, it should be first placed upon the platform and balanced by a suitable counterpoise. It should then be removed and standard weights substituted until the same balance is established as before. The weight of the object will then be equal to the weights substituted for it.

The method of substitution weighing is rendered precise by observing certain details which are explained in the following portions of the paper, where they will be taken up in the order in which they present themselves for consideration in using this plan of weighing.

3. PREPARATION OF THE SCALE FOR WEIGHING

The scale should rest level on a solid support. The parts should be examined and aligned, all binds should be removed, and all antifriction contacts should be cleared. Provisions should be made for applying and removing the loads without disturbance, so that the relative positions of the scale parts will not be altered, and the loads should be carried on the platform or pan in such a manner that their weight will always have the same distribution among the supporting main load knife-edges.

4. PROVISION FOR READING THE POSITION OF THE BEAM

A means must be supplied for reading the angular position of the beam. This is already provided for in the construction of the common even-arm laboratory balance by a pointer attached to the beam and arranged to read on a ruled scale. In many laboratories the image of a stationary ruled scale on a distant wall or support is reflected into an observing telescope by means of a mirror mounted on the beam. This is a very simple and effective method where the telescope and scale are available, and as this arrangement is perfectly practical for the shop the scale man should familiarize himself with it. For the ordinary case in substitution weighing on compound lever scales it is recommended as the simplest practical scheme to provide for reading the beam by mounting a graduated scale on the beam and a pointer on the trig stand, so that the angular position of the beam can be read in divisions on the graduated scale. Such an arrangement is shown in Fig. 1. Where a reverse arrangement is employed and the pointer is mounted on the beam and the reading scale is mounted on the trig loop, it is necessary to follow the motion of the beam by moving the eye up and down. This method is more trying to the observer and less

accurate on account of variations in illumination. Experience shows that it is distinctly better to use the moving scale and stationary pointer.

The reading scale and pointer should be so disposed that when the lever is balanced in a horizontal position the reading will be some simple value like 10 or 20, and the stops limiting the angular movement should be such that the play is equal on either side of this horizontal position.

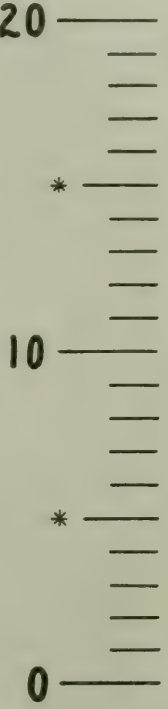

FIG. 2.—*Proportion of scale graduations suitable for mounting on the beam for reading its position in weighing by substitution*

5. CHOICE OF THE RULED SCALE

For making the readings a decimally graduated scale should be used. In this scale the length of the lines will have an important influence on the ease and accuracy with which they can be read. The particular form recommended is where the length of the ordinary graduations is about one and one-half times the distance between their centers, every fifth line about two times this distance, and every tenth line about three times this distance. With relatively longer lines for the graduations it is found that the eye tends to become confused and may not recognize the scale division until the time for making the reading has passed. An example of the scale recommended is shown in Fig. 2.

It has been found that a suitably graduated millimeter scale serves excellently this purpose. With proper lighting it is found that the readings can be estimated to 0.1 millimeter comfortably and consistently. The paper millimeter scales such as are provided at the Bureau of Standards are convenient; short sections can be cut out and attached to the beam. The weight is small, and the effect on the period and inertia of the beam of large scales is entirely negligible.

6. READINGS SHOULD INCREASE WITH WEIGHT

The values or markings selected for the graduation should be such that an increase in the weight being standardized will correspond to an increase in the reading. If the substitution weighing is being made for weights placed on the platform, then the scale

should be arranged to give increased readings as the beam moves up. If the substitution weighing is being carried out on the counterpoise, then the reading should be arranged to increase as the beam descends.

7. AVOIDANCE OF PARALLAX

If the pointer is well in front of the ruled scale, the exact reading will depend on the position of the eye, as indicated in Fig. 3. This effect is called parallax. The design and position of the pointer should be such that this is reduced to a negligible amount. This can be done by placing the pointer near to the scale; by having the pointer of such a design that it will help the observer to place his eye squarely in front of it; by the use of a mirror back of the pointer which will enable the eye to be placed properly (by moving the eye and lining up the pointer or shaft with its reflection); or by other methods which local circumstances will often suggest.

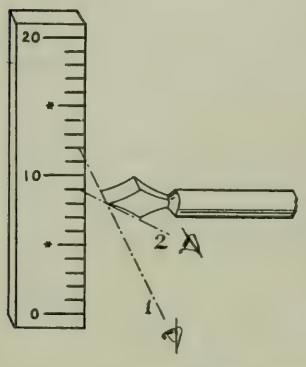

FIG. 3.—*Diagram illustrating parallax*

The pointer is well in front of the scale, and the reading depends upon the particular line of sight fixed by the eye. The proper reading is 12 0, as observed from position 1, where the line of sight is perpendicular to the scale. In position 2 the eye is too high and the pointer appears to read 9.0

8. THE ESTIMATION OF TENTHS

The position of the beam is read as so many divisions and so many decimal fractions of a division. The fractions are estimated to the nearest tenth of a division by observation. This can be done by anyone with a little practice. In estimating tenths, however, it is important that a decision be made at once and without hesitancy. It may be better that an error of a tenth or even two-tenths be made than to miss an observation and lose time in taking the observation over again. It is also found in practice that the most accurate and consistent estimations are made when it is done promptly, and that too much care, when it results in indecision and delay, actually causes a decrease in accuracy.

9. PERIOD OF VIBRATION OF THE BEAM

With the use of the pointer and scale the position of the beam can be read to a high degree of relative refinement. In fact, the sensibility is often such that the action of the beam can be quickened and time can be saved by lowering or even in some cases removing the balance ball, and yet it will be possible to read to the

required accuracy. The beam, however, should not be caused to act too quickly. The observer should be allowed plenty of time to record the observations. If the readings are being made by one person and recorded by another, it is possible to have a much faster beam. However, there may be no particular gain in this, as it will be necessary to stop and make computations before proceeding with the test. A period of 15 seconds is recommended. By period is meant the time required for the beam to swing to and fro through a complete cycle.

10. THE REST POINT EXPLAINED

In rough forms of scales the position of balance is obtained by allowing the beam to come to rest. In the present instance, however, where precision is desired, and except in special forms of balances which it is not the purpose to discuss here, it is not practicable to determine the position of equilibrium by allowing the beam to come to rest. It is, however, possible to determine from the moving pointer where the beam would come to rest, and this point or position is known as the *rest point.*

If there is but very little friction present either in the knife-edges and connections or in the damping action of the air, the pointer will vibrate practically an equal distance on either side of the rest point. If the means for reading are sensitive enough, however, it will be found that the magnitude of the excursions of the pointer will gradually die down. The method for determining the rest point described in this paper takes into account the effect of this damping.

11. DETERMINATION OF THE REST POINT

The rest point is found from the moving beam by reading the extreme positions of the pointer as it swings and combining the readings in a certain simple manner. Thus, in Table 1, we have a series of readings taken in order:

TABLE 1

Observation number	Readings of the pointer		Observation number	Readings of the pointer	
	Low position	High position		Low position	High position
1	2.0		4		27.0
2		29.0	5	6.0	
3	4.0		6		25.0

It will be noted that each downward swing is two divisions less in amplitude than the one before, as is indicated by an increase in

the successive figures, and that the successive upward readings also diminish by two divisions. This is on account of damping. The observations are used in such a manner as to eliminate the effects of this damping. For obtaining the rest point the following simple rules are given:

1. Use the observations in the order taken.

2. The first and last observations used in the computation should be at the same end of the swing—that is, in the same column.

3. Half the sum of the averages of both columns will be the rest point.

For example, we can use the observations just given in a number of different ways for obtaining the rest point. Using observations 1, 2, and 3 we have:

	Low	High
	2.0	....
	4.0	29.0
Average.....	3.0	....

One-half the sum of 3.0 and 29.0 is 16.0, which is the rest point. Again, using observations 1, 2, 3, 4, and 5, we have:

	Low	High
	2.0	29.0
	4.0	27.0
	6.0	....
Average.....	4.0	28.0

and $4.0 + 28.0 \div 2 = 16.0 =$ rest point.

Or we could take observations 2, 3, 4, 5, and 6, in which case there results:

	Low	High
	...	29.0
	4.0	27.0
	6.0	25.0
Average.....	5.0	27.0

and $5.0 + 27.0 \div 2 = 16.0 =$ rest point.

In the example just considered the damping of successive movements in each case was the same. In many balances, however, the amount of this damping falls off as the amplitude dies down, with the result that there is a small theoretical error in the determination of the rest point even when several observations are employed.

For most purposes the rest point can be determined with sufficient accuracy by using three consecutive observations—one on one

side and two on the other. The rule should be to start recording observations and continue until it is clear that the successive swings of the beam are uniform and consistent in character. Generally it is necessary to take only four readings. In this case the first reading serves as a check on the third, but it is not used in the computations, which fact is indicated by the use of brackets [] or, in practice, by striking a line through the figures.

12. USE OF EVEN VALUES IN ROUNDING OFF FIGURES

There is very frequent occasion to round off figures. For instance, in the following illustration the values are not recorded or computed, as a rule, to a greater refinement than 0.1 division. In obtaining the averages, however, it is a very common thing to get a value in the next place. The result is then usually rounded off to the nearest 0.1, but frequently the figure 5 appears in the decimal place to be dropped. Thus, in the series of readings:

Low	High
(1) . . . [16.3]	(2) 22 6
(3) . . . 16.5	(4) 22.5

The mean of 22.6 and 22.5 is 22.55. In rounding off, the value derived would be either 22.5 or 22.6. *The rule*, in this case where the last figure is 5 and where it is therefore equally accurate to round off to either the higher or lower figures, *is to round off to the nearest even number*, so the number selected would be 22.6. This would then be averaged with 16.5, as $(22.6 + 16.5) \div 2 = 19.55$, which, applying again the rule just given, would be recorded and used as 19.6.

The merit of this rule is that it is easy to remember, simple to apply and follow, it results just as often in increasing the value as in decreasing it, and it is possible by using this rule for different individuals working separately to take the same data and work it out in the same manner and arrive at the same conclusion. The odd values could be used instead of the even values, but custom has ordered otherwise. For cases where more than two numbers are averaged other decimal places may appear, but no difficulty should be encountered in determining what should be done in rounding off.

13. UNNECESSARY TO DIVIDE BY 2

In what has been given in the preceding discussion the rest point is obtained by dividing the sum of the average readings of the pointer on either side by 2. In practice it is not necessary to do this, but the undivided sum of the average readings of each column is used. This saves time by reducing the computations by

one step. In the illustration just given above, the sum 22.6 + 16.5 = 39.1 would be taken instead of half the value, or 19.6. The number employed is therefore twice the actual rest point or, as it may be referred to, it is the number of half divisions of the actual rest-point reading. This introduces no error, as the subsequent computations are carried out consistently with regard to this practice.

14. THE SENSIBILITY RECIPROCAL

The sensibility reciprocal, or the *sr*, as it will be written, is defined as the change in weight required on the load-receiving part to change the reading of the rest point one division on the graduated scale. On account of not dividing by 2, the value actually employed in the computations is not the *sr*, but one-half the *sr*, or it is the weight required to change the actual rest point one-half of a division. The *sr* is obtained by changing the small weights, so that the rest point will be altered several divisions. Thus, in Table 2, there is obtained:

TABLE 2

Readings		Value taken for rest point	Load
Low	High		
[16.2]	24.7	.....	10-pound standard in pan
16.2	24.6	.....	
16.2	24.6	40.8	
[21.9]	28.4	.....	10-pound standard in pan +10.0 grains
22.0	28.2	.....	
22.0	28.3	50.3	

50.3 − 40.8 = 9.5 half divisions = 10 grains.

$$1/2\ sr = \frac{10}{9.5} = 1.05 \text{ grains.}$$

For a given condition of loading and for a given load the value of the *sr* should remain substantially constant. It is recommended that the *sr* be taken for each load, and that in the computations each load be figured with the corresponding *sr*, and that average values be not used. The advantage of taking the *sr* each time is that if there is an error in reading the position of the pointer this fact will be disclosed by the obtaining of a value for the *sr* which is inconsistent with the values obtained at other times.

The *sr* should remain constant throughout the angle of the play of the beam. If this is not the case, there is some interference or imperfection which should be eliminated before the balance is used in actual weighing.

15. POSITION OF CENTER BALANCE DETERMINED BY COMPUTATION

In the method described here it is always determined what small weights would be required on the load-receiving part, platform, or counterpoise, in addition to the standard weight or object, to cause the pointer to reach a mid-balance position or to have a rest point in the middle reading of the scale. This could be accomplished by adding or removing small weights until this was established by trial; but in the plan given here time is saved and the action of the scale is made a matter of record by observing the rest point for two values of the small weights and then *computing* the amount of small weights required to bring the rest point to the mid-scale position.

It has been previously mentioned that under proper conditions the *sr* for a given load will be constant throughout the play of the beam. This is equivalent to assuming that the change in the rest point is proportional to the change in the small weights of the load. It should be easily understood that when this condition obtains it is a simple matter to compute the change in weights required to establish the center balance when the rest point for a given load is known together with the *sr*, or in this case one-half the *sr*. As the details of this are covered in the description of the record form and computation sheet, space will not be taken to illustrate the matter here.

16. RECORD FORM AND COMPUTATION SHEET

For recording data and making the computations the accompanying form, Table 3, can be used to advantage. This has been developed as the result of a careful study of the matter and from the desire to secure a record form and computation sheet uniform with that used in making precision tests on railroad master scales and grain scales. In securing this uniformity a few extra computations are needed compared with the method which has been used in the laboratories of the Bureau of Standards. This form was evolved, however, as a result of a belief very emphatically expressed by several practical railroad scale men that the form should be made as nearly uniform with the other one mentioned as possible, a point of view to which the writer has been converted after first holding a contrary belief, especially since the use of this form in the field by him recently has demonstrated its convenience.

TABLE 3.—Form for Recording Observations and Making Computations in Substitution Weighing

[This form has been arranged to facilitate its understanding and use by the ordinary scale man by making it as similar as possible to that used for the precision test of railroad master and grain scales.]

Place..... Date..... Observer..... Test No..... Page....

Identification of weights tested..... Standard wts..... Car No.....

Balance used..... Temperature..... Computed by..... Checked by.....

Observation number	Time	Beam readings: Low	Beam readings: High	Beam readings: Sum = rest point ×2	20− sum	½ sr	Balance correction = 6×7	Load: Identification	Load: Additional small weights	Correction to standard weights	Small weights for center balance: Standard, 8+10C+11	Small weights for center balance: Unknown, 8+10	Correction for unknown = 12−13	Computation for ½ sr and notes
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
371	4:47	[5.9] 6.0	8.9 8.8	14.8	+5.2	0.633	+3.29	10-pound standard	10 grains	+2.10 grains	15.39			
372		[12.1] 12.3	18.3 18.3	30.6	−10.6			do	do +10 grains					$\frac{1}{2}$ sr = $\frac{10}{15.8}$ = 0.633
373		[7.4] 7.4	10.2 10.0	17.5	+2.5	.625	+1.56	10-pound No. 4	10 grains			11.56	+3.83 grains	
374	4:57	[12.2] 12.3	21.2 21.1	33.5	−13.5			do	do +10 grains					$\frac{1}{2}$ sr = $\frac{10}{16.0}$ = 0.625

After the scale mechanism and all other details are ready for the test the standard weight should be placed upon the load-receiving platform or counterpoise, as the case may be, together with a small weight or two sufficient in amount to cover any probable variation between the standard and the other weights to be compared with it. The scale should then be balanced approximately by applying suitable material, and this counterpoising material should then remain undisturbed during the remainder of the test. The balance of the scale before the standard load is applied is of no importance in the method of test described here.

The record form and computation sheet will now be explained: The first column is for the computation number. Each series of weighings or swings taken together should be given a computation number. Numbers are found to be very convenient for reference and for identifying various data obtained. The second column is provided for recording time. It is not necessary that this be filled in for each observation. Columns 3 and 4 are used for recording the positions of the pointer at the extreme positions of its swing. The position for the lowest numerical readings are placed in 3, marked "low," and the positions of highest readings are recorded in 4, marked "high." The sum of the average low and high readings is placed in column 5. The resulting number is twice the reading for the rest point. In column 6 is placed the result of subtracting the value in column 5 from the number 20. Where the value in column 5 exceeds 20, the difference in column 6 should, of course, be given a negative sign. This assumes that the direct reading of the rest point is 10 in its mid-position, or that twice the reading of the pointer in this position, as would appear in column 5, is 20. If this is not the case, the number corresponding to twice the actual reading for the mid-position of the pointer on the reading scale should be used in place of 20.

The value in this column 6 represents the amount by which the rest point, as recorded in column 5, will have to be changed to bring the beam to balance in its mid-position, where the rest point will appear as 20. The value of one-half sr is recorded in column 7. The determination of this, of course, must await until two series of observations are taken corresponding to a known difference of weight on the load, pan, or platform. The computation for this one-half sr is usually made in column 15 at the extreme right. The theoretical weight change required to be added

to the platform to produce mid-balance position of the pointer is given in column 8. This is equal to the product of columns 6 and 7. It is the weight that should be added to or subtracted from the pan according to whether the sign is plus or minus, to change the rest point from the value observed, to a center position on the scale.

The character and identification of the weights are given in column 9. The small weights which are placed in the pan, in addition to the standard weight or weight being tested, are entered in column 10. In column 11 are recorded the corrections to the standard weights, which, of course, are known.

In column 12 is recorded the amount of small weights in addition to a perfect standard weight which would be required to bring the rest point to its mid-position. It relates to the standard weight only. It is equal to the sum of the quantities in columns 8, 10, and 11, with due regard for sign. This weight required may, of course, be negative. Column 13 is used only for data for the unknown weight. It represents the sum of the values given in columns 8 and 10 for the unknown weight. It represents the small weights required on the pan, in addition to the unknown weight, to bring the position of equilibrium of the pointer to the mid-position of the scale.

Column 14 is for the correction of the previously "unknown" weight. The value in column 13 subtracted from the value of the standard weight in column 12 is the correction for the weight which is being standardized.

On the form are given the results of a test made to standardize a 10-pound weight, here designated as 10-pound weight No. 4. With the standard and 10 grains placed on the pan observation 371 was made.

The time is recorded in column 2 and the readings of the pointer are entered, in accordance with the principles previously given, in columns 3 and 4. Four observations are taken, and it appears that the change in the successive readings for the lower observations is consistent with the difference in the two readings for the high positions. This indicates that no mistake has been made, and that there is no excessive or irregular damping. The rest point is obtained by adding the value of 6.0 in column 3 to the average of the two readings in column 4. The first reading of 5.9, indicated in brackets, is not used in the computation. The result

is 14.8, which is put in column 5. Subtracting 14.8 from 20.0 the value of +5.2 results, which is placed in column 6.

Meanwhile, in column 9 has been entered the identification of the weight, and in column 10 the additional small weights used with it—in this case 10 grains—are recorded. The correction to the 10-pound standard weight is +2.10 grains, which is placed in column 11.

Following the first observation 10 grains are added to the weight pan, as indicated in column 10 of observation 372, and the rest point is determined, as before. It appears that the rest point is changed from the previous value of 14.8 to 30.6, or 10 grains has caused it to change 15.8 half-divisions. The value of one-half *sr* is then computed, as indicated in column 15, and the value obtained for it of 0.633 is entered in column 7. The product of the values in columns 6 and 7 is placed in column 8. In this case it is $+5.2 \times 0.633 = +3.29$. This signifies that 3.29 grains added to the pan for the conditions of observation 371 should bring the rest point to the center of the scale, so that it would appear in column 5 as 20.0.

In column 12 is placed the sum of the values in columns 8, 10, and 11, which is 15.39. It represents the weights in addition to a perfect 10-pound standard on the pan which would be necessary to bring the rest point $\times 2$ to the value 20.

The unknown weight is then substituted and observations are made as before, which are recorded in observations 373 and 374. By this means it is determined that the unknown weight would require in addition to itself 11.56 grains on the pan to establish for the double rest point. This is obtained by taking the sum of the values in columns 8 and 10 and entering it in column 13.

The unknown weight is heavy. In the previous observation it was determined that 15.39 grains would be required on the pan for center balance in addition to a perfect 10-pound standard. The unknown weight only requires 11.56 grains to establish this condition. It is therefore heavy, or has a plus correction. The value of this correction, +3.83 grains, is recorded in column 14 and is obtained by subtracting the value in column 13 for observation 373 from that given in column 12 for observation 371.

In observation 373 a weighing was carried out similarly to that previously done in observation 371. It would be possible at this point to determine the value for the unknown weight without

requiring additional data to be taken. However, in compliance with the practice recommended here, that the *sr* be obtained each time, an additional observation is made, observation 374, by which the *sr* is again determined. This reduces very largely the chance for an observational error remaining undetected. Here 10 grains produce a change in the rest point of 16.0 divisions, where in the previous case it was 15.8 divisions. The difference is but 0.2 division, and the agreement is quite satisfactory, which indicates both that the apparatus appears to work properly and that no mistake has been made in the readings.

This same form and the same method of procedure is adaptable to practically all needs for substitution weighing that will ordinarily arise. The modifications or the special considerations required in weighing with other forms of apparatus are of such a simple character and of so obvious a nature as to make it unnecessary to refer further to them here.

17. SUMMARY

In conclusion it may be stated that the plan of substitution weighing presented here not only can be used with laboratory precision apparatus, but, what is of more importance here, it offers a means for obtaining weighings of considerable refinement with ordinary forms of compound-lever scales that are often available. Large weights or objects can be weighed, or fine laboratory weights can be tested and calibrated by following the outline of substitution weighing given herein. The form will be found simple to follow and use, particularly by those who are familiar with the form used by the Bureau of Standards in the test of railroad master and grain-hopper scales.

WASHINGTON, October 8, 1921.

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THERMAL STRESSES IN CHILLED IRON CAR WHEELS

BY

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Bureau of Standards

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in design. Perhaps the chief factor toward enabling the chilled-iron wheel to meet operating conditions was the adoption of standard designs. As a result the percentage of failures when considering the number of wheels in service is less to-day than it was before the adoption of the standards and has been steadily growing less while operating conditions have been growing more severe.

Some slight variations exist in the making of wheels by different manufacturers. A brief description of the method of making a chilled-iron wheel follows. The materials charged into the cupola consist of scrap wheels, pig iron, and special alloys, in which the proportions are varied to produce a metal which will have satisfactory chilling qualities and sufficient strength to satisfy the service requirements. After tapping the iron from the cupola it is cast directly into wheels. The iron for the tread of the wheel is poured against iron chillers, while the remainder of the mold is made up of sand. This method of molding produces white or chilled iron, which is extremely hard and capable of resisting both wear and deformation in the tread, while the remainder of the wheel is composed of soft and easily machined gray cast iron. After casting, the wheels are left in the molds 15 to 60 minutes, depending on the weight of the wheel. The lighter wheels remain in the mold the minimum and the heavier ones for the maximum length of time. At the time of stripping the mold the interior parts of the wheel are at a temperature of approximately 925° C (1697° F) while the surface is about 700° C (1292° F) to 760° C (1400° F).

The method of molding, whereby a portion of the metal is poured against a chiller, results in the metal being solidified at different times at various positions within the wheel. For instance, the metal poured against the chiller sets very quickly after contact with the chiller, while the metal poured against the sand parts of the mold take a longer time to solidify. As a result the wheels cast in this way contain internal strains and stresses when taken from the mold. In order to reduce or eliminate the internal stress, the wheels after taken from the molds (at temperatures as indicated above) are placed in deep circular pits which will accommodate 10 to 20 wheels. After placing the wheels in the pits the pits are covered and sealed and the wheels left therein from two to five days. By this process, called "annealing" or "pitting," the inequalities in temperatures of the wheel are removed, as are also a

very considerable portion of the internal stresses. The temperature of the wheels upon removal from the pits is from 90 to 315° C (194 to 599° F). After being taken from the pits the wheels are placed in a room in close formation and allowed to cool slowly to room temperature. These rooms are generally inclosed to prevent undue air circulation. To illustrate the effect of annealing, it may be stated that a wheel if allowed to cool in air after removal from the mold will most certainly crack on account of internal stresses, whereas a wheel after being properly annealed will not crack from the internal stresses still present (if any), but its internal structure has been so modified that it will withstand the stresses produced through static load, flange pressure, brake application, impact, etc., as found in service. The operation of annealing is an important one and is a large factor in the manufacture of good wheels.

After the wheels are cooled to room temperature they are cleaned by sand blast and then inspected to see if they satisfy the specifications[1] of the buyer. After passing inspection the hubs are bored, the wheels then mounted on axles, and they are then ready to be placed in service.

Chilled-iron wheels have given general satisfaction, even under the present existing conditions of greater speeds and increased stresses due to the use of heavier wheel loads. With the advent of more severe operating conditions there are frequently cases of improper usage in which the car wheels are subjected to conditions much more severe than the service for which they are designed. Through such conditions it is found that occasional failures of chilled-iron wheels occur at the foot of long, steep grades as found in mountainous regions. This particular type of failure is caused by prolonged brake application at high speed and the absence of cooling stations. The effect of long-continued application of the brakes is to heat the tread of the wheel to high temperatures, while the central portion or hub of the wheel remains relatively cool. At points intermediate between the tread and hub the temperature decreases from that of the tread to that of the hub. The rate of decrease, in general, is not uniform and varies at different positions within a wheel. These variations in temperature as caused by brake application induce stress and strain of varying amount within the wheel.

[1] The specifications generally are those as determined by the American Railway Association (mechanical division).

The magnitude of these stresses and strains depends on the rate of heating the tread of the wheel, which in turn is dependent on the brake-shoe pressure, speed of train, kind of shoe, and time applied. When the difference in temperature between the tread and hub becomes sufficiently large, the wheels will crack and occasionally break in parts, with the possibility of derailing the car and wrecking the train. One of the large railroad systems found that in a period of seven months approximately one-fifth of their wheel failures were due to the effects of brake application. As stated above, this type of wheel failure usually occurs through improper usage, and investigation generally reveals either excessive speed with brake heavily applied when descending long grades, improperly maintained braking equipment, whereby one car does more than its share in retarding the train, or the absence of cooling stations, whereby the train may be stopped and the temperatures allowed to equalize. Although the number of failures of chilled-iron car wheels is relatively small, yet they are of sufficient importance to warrant investigating the strains and stresses that are developed under various operating conditions with a view toward improving the design and harmonizing operating conditions with design. For these reasons it was decided after consultation with representatives of the Association of Manufacturers of Chilled-Iron Car Wheels to conduct at the Bureau of Standards an investigation of the thermal stresses in chilled-iron car wheels.

Innumerable problems present themselves in connection with the subject of strain or stress due to brake application; as, for instance, the effect of speed and shoe pressure and length of brake application in producing thermal strain. Accordingly, this investigation has been restricted to the problem of determining the manner in which the thermal stresses build up in wheels and chiefly to determine the relative ability of the various weights of chilled-iron wheels to withstand the effects produced by temperature gradient within the wheel.

II. GENERAL PLAN OF INVESTIGATION

1. DISPOSITION OF WHEELS

Fifty wheels were used in this investigation, and in order to make the tests general the wheels were furnished by three different manufacturers, designated A, B, and C, instead of by name. Each manufacturer was requested to supply four wheels of each

weight or type which he wished to submit. One of these was used for drop and one for thermal tests (American Railway Association Specifications) at the works of the manufacturer and the remaining two wheels for special Bureau thermal stress tests. The drop and thermal tests made at the foundries were of the usual type required by current specifications for chilled-iron car wheels.[2] Manufacturer A cast wheels for the special Bureau of Standards tests only, but the other manufacturers provided wheels for all tests.

2. DESIGNS AND WEIGHTS OF WHEELS TESTED

Three types of wheels were tested in this investigation, namely, the Washburn, arch-plate, and single-plate types. A cross sectional drawing of the Washburn, commonly called the M. C. B. type, is shown in Fig. 1. In Figs. 2 and 12 are shown, respectively, the arch-plate and single-plate types. The M. C. B. was the standard shape adopted by the Master Car Builders' Association in 1909, and although many of this type are still in service it has been replaced by and all renewals are of the arch-plate type. The chief difference between the two types is in the cross section, as will be apparent from Figs. 1 and 2. The present M. C. B. standard wheels are of the arch-plate design and weigh 650, 700, 750, and 850 pounds for cars of 30, 40, 50, and 70 tons, respectively. The single-plate type (Fig. 12) is a special experimental design

[2] DROP TEST.—The wheels shall conform to the following drop-test requirements: The test wheel shall be so placed on the three supports, with flange turned downward, that the tup will strike centrally on the hub. When tested in accordance with the following conditions, the wheel shall stand the following specific number of blows:

Weight of wheel in pounds	Weight of tup in pounds	Height of drop in feet	Number of blows	Weight of wheel in pounds	Weight of tup in pounds	Height of drop in feet	Number of blows
625	200	9	10	725	200	12	12
700	200	10	12	850	200	15	12

DROP-TEST MACHINE.—The three supports shall not be more than 5 inches wide. The anvil shall be supported on rubble masonry at least 2 feet deep and shall weigh not less than 1700 pounds. The striking face of the tup shall be 8 inches in diameter and be flat.

THERMAL TEST.—Should the test wheel stand the given number of blows without breaking into two or more pieces, the inspector will then subject the other wheel to the following test:

(*a*) *Preparation.*—The wheel shall be laid with the flange downward in the sand and a channelway 1¾ inches wide and 4 inches deep must be molded with green sand around the wheel. The clean tread of the wheel must form one side of the channelway, and the clean flange must form as much of the bottom as its width will cover.

(*b*) *Test.*—The above-described channel must be filled with molten cast iron, which shall be hot enough when poured so that the ring which is formed when the metal is cold shall be solid or free from wrinkles or layers. The time when pouring ceases must be noted, and two minutes later an examination of the wheel must be made. If the wheel is found broken in pieces, or if any cracks in the plate extend through or into the rim, all wheels of the same tape size as the wheel broken will be rejected.

and is not at present used by any railroad. For purposes of convenience the wheels were given serial numbers 1 to 50, inclusive. Wheels 1 to 28, inclusive, were tested at the Bureau of Standards and are described in Table 1, while wheels 29 to 50, inclusive, were tested at the place of manufacture. Wheels 29 to 39, inclusive, were subjected to drop test (Table 2), and 40 to 50, inclusive, were used for the ordinary thermal test (Table 3).

Manufacturer A furnished three types of wheel, B supplied four, and C furnished seven different types.

TABLE 1.—Description of Wheels Tested at Bureau of Standards

Type	Wheel number	Manufacturer	Weight	Tape size [a]	For drawing see Figure—
			Pounds		
M. C. B.[b]	1	A	625	.....	1
Do	2	A	625	.....	1
Do	3	A	700	.....	2
Do	4	A	700	.....	2
Do	5	A	725	.....	3
Do	6	A	725	.....	3
Arch plate	7	B	625	2	4
Do	8	B	625	2	4
Do	9	B	700	2	5
Do	10	B	700	2	5
Do	11	B	775	3	6
Do	12	B	775	3	6
Do	13	B	850	3	7
Do	14	B	850	3	7
M. C. B	15	C	625	2	8
Do	16	C	625	2	8
Arch plate	17	C	650	2	9
Do	18	C	650	3	9
M. C. B	19	C	700	3	10
Do	20	C	700	3	10
Do	21	C	725	4	11
Do	22	C	725	4	11
Single plate	23	C	750	4	12
Do	24	C	750	4	12
Arch plate	25	C	775	4	13
Do	26	C	775	4	13
Do	27	C	850	5	14
Do	28	C	850	4	14

[a] No tape-size measurements were furnished by foundry A.
[b] Present standard wheels adopted by Master Car Builders' Association are 650, 700, 750, and 850 pound weights of arch-plate type.

TABLE 2.—Results of Drop Tests Made by Manufacturers [a]

Type	Wheel number	Manufacturer	Weight	Tape size	Average depth of chill	Result of test
			Pounds		Inches	
Arch plate.....	29	B	625	2	11/16	Satisfactory; at the sixth blow a crack developed in the backplate; the front plate cracked at the twelfth blow; the wheel cracked in two pieces at the fourteenth blow.
Do.....	30	B	700	3	5/8–3/4	Satisfactory; a slight crack was apparent in backplate on twenty-eighth blow; the wheel cracked through the tread on the thirty-second blow, and the wheel broke into two pieces on the sixty-sixth blow.
Do.....	31	B	775	3	5/8–3/4	Satisfactory; at the sixteenth blow a slight crack developed in the backplate, and at the twenty-first blow the cracks extended to the tread; at the twenty-ninth blow the wheel broke in two pieces.
Do.....	32	B	850	3	5/8–3/4	Satisfactory; at the eighteenth blow the wheel cracked through the tread; it broke into three pieces at the forty-sixth blow.
M. C. B.....	33	C	625	1	1	Satisfactory; twenty-fifth blow, no break.
Arch plate.....	34	C	650	2	3/4	Do.
M. C. B.....	35	C	700	3	1/2	Do.
Do.....	36	C	725	4	3/8	Do.
Single plate.....	37	C	750	4	3/8	Satisfactory; broke at twenty-first blow.
Arch plate.....	38	C	775	4	1/2	Satisfactory; twenty-fifth blow, no break.
Do.....	39	C	850	4	7/16	Do.

[a] No drop tests were made of wheels furnished by manufacturer A.

TABLE 3.—Results of Thermal Tests Made by Manufacturers [a]

Type	Wheel number	Manufacturer	Weight	Tape size	Average depth of chill	Result of test
			Pounds		Inches	
Arch plate.....	40	B	625	3	11/16	Satisfactory; no break in 3½ minutes.
Do.....	41	B	700	3	5/8–3/4	Satisfactory; no break in 4 minutes.
Do.....	42	B	775	2	5/8–3/4	Do.
Do.....	43	B	850	4	5/8–3/4	Do.
M. C. B.....	44	C	625	2	1/2	Satisfactory; no break in 5 minutes.
Arch plate.....	45	C	650	1	7/16	Do.
M. C. B.....	46	C	700	3	1/2	Satisfactory; no crack.
Do.....	47	C	725	3	7/16	Do.
Single plate.....	48	C	750	3	1/2	Do.
Arch plate.....	49	C	775	4	3/8	Do.
Do.....	50	C	850	3	7/16	Do.

[a] No thermal tests were made of wheels furnished by manufacturer A.

III. TESTS AT PLACE OF MANUFACTURE

The tests at foundry B were made in the presence of a Bureau representative, while the tests at foundry C were made in the presence of the foundry engineer. No tests were made at foundry A, as stated previously.

1. DROP TESTS

The results of the drop tests, together with the tape size and depth of chill, are shown in Table 2. By comparison with the requirements of the drop test as given in the car-wheel specifica-

tions [3] it will be noted that all the wheels—namely, four wheels from manufacturer B and the seven wheels from foundry C—gave satisfactory results in the test. The weakest wheel of those tested was the 625-pound wheel furnished by manufacturer B. This maker stated that all 16 wheels furnished by him for this investigation were made from the same heat, with the object of giving comparative results by reducing the number of variables. He predicted before the tests were made that the light wheels would not be as satisfactory as the heavier ones, as it is his ordinary practice to make the lighter-weight wheels of slightly higher silicon content than the heavier wheels.

The drop tests at foundry B were carried to destruction; that is, until the wheel broke into two or more pieces. At foundry C, however, the tests were discontinued at the twenty-fifth blow.

2. THERMAL TESTS

Upon examination of the results of the thermal tests in Table 3 and by comparison with the specification it will be seen that all of the wheels satisfactorily met the requirements. As in the case of the drop tests, the 625-pound wheel from foundry B was the weakest wheel. The tape size and depth of chill of these wheels are also shown in Table 3.

IV. TESTS AT BUREAU OF STANDARDS

The 28 chilled-iron car wheels sent to the Bureau were subjected to a special thermal stress test approximating severe service conditions, yet so conducted as readily to permit the taking of the necessary strain and temperature measurements.

1. METHOD OF PROCEDURE FOR THERMAL STRESS TESTS

In the special thermal stress tests the wheel was mounted on a hollow water-cooled 6-inch axle. The axle in turn rested upon cast-iron and concrete supports, such that the bottom of the wheel was 2 feet 8 inches above the floor. A soft-steel resistor 3½ inches in width and one-fourth inch in thickness was placed on the tread of the wheel, but insulated from it by a thin sheet of perforated asbestos, and an alternating current of 1000 to 1500 amperes at 15 to 30 volts from a 30-kva transformer was passed through the resistor. As the wheel was in an upright position and remained stationary throughout the test, it was readily possible to take such observations as necessary. Fig. 15 shows the

[3] See footnote 2.

arrangement of this apparatus. It was found possible to bring the resistor itself to a red heat within 5 to 10 minutes. Undue radiation of heat into the air was prevented by the use of asbestos covering. The tread of the wheel attained a maximum temperature of approximately 380° C (716° F) in each experimental run.

In order to interpret the results of these tests, it was necessary to determine satisfactorily the distribution of temperature in the wheel from tread to hub. Copper-constantan thermocouples of No. 30 B. and S. gage wire were used—seven couples along a vertical radius at approximately 2-inch intervals and seven others similarly located along the horizontal radius. Readings were taken along both radii for the purpose of obtaining duplicate results. Two other thermocouples were inserted into the treads of the wheel. Thus, four couples, one at the gap in the resistor, were placed at equidistant points in the tread of the wheel and assurance given that uniformity of tread temperature was attained. The 16 copper-constantan thermocouples can be seen in Fig. 15, extending from the wheel to overhead supports and then down to the potentiometer on the transformer table.

A 2-inch Berry strain gage was used for measuring the deformation, six sets of readings being taken at 1-inch intervals on both the vertical and horizontal radii. It will be observed that these readings were taken over a considerable area, this being the only manner of satisfactorily determining the location of the point of maximum stress. A better understanding of the location of the points at which strain gage and thermocouple readings were taken can be obtained from Fig. 16.

It was only necessary to take a survey of the stresses on the plate side of the wheel (outside as mounted on axle), since preliminary measurements had shown that the stresses on the bracket side of the wheel were of a compressive nature and of relatively small magnitude.

Identical rates of power input were maintained for each test in order to obtain comparative results. It was necessary to increase the power input near the end of the test to attain the desired tread temperature in a comparatively short time.

The rate of heat input in these tests was considerably more severe than that found in normal operating service. Table 4 shows the schedule of power supplied to the resistor for all of the tests. It does not, however, indicate the exact amount of work performed on the wheel, as a portion of the heat input is lost through radiation.

TABLE 4.—Power and Energy Supplied to Resistor

Time from start (minutes)	Kilowatts	Total kilowatt-hours	Million foot-pounds	Time from start (minutes)	Kilowatts	Total kilowatt-hours	Million foot-pounds
10	8.7	1.45	3.85	70	16.8	17.05	45.27
20	15.0	3.95	10.49	80	17.4	19.95	52.97
30	15.0	6.45	17.12	90	18.0	22.95	60.93
40	15.0	8.95	23.76	100	18.0	25.95	68.90
50	15.6	11.55	30.67	110	18.0	28.95	76.86
60	16.2	14.25	37.83	120	18.0	31.95	84.83

From the above table it will be noted that the power input was not uniformly applied. The amount applied per minute during the different periods of the test was as follows:

	Foot-pounds
First half hour	570 000
Second half hour	690 000
Third half hour	770 000
Fourth half hour	797 000

Table No. 5 gives an approximate comparison between the work performed on the test wheels and the energy required to hold a train at a constant speed on descending grade. This table shows the brake work per wheel in millions of foot-pounds per mile for cars of various capacities and grades up to 4 per cent.

TABLE 5.[a]—Brake Work Per Wheel Per Mile (in million foot-pounds per mile[b]) for Constant Velocity on Various Grades for Various Car Capacities and Wheel Loads

Car capacity	60 000	80 000	100 000	120 000	140 000	160 000	180 000	200 000
Maximum wheel load (tons)	6	8	10	11.25	12.5	14.75	15	16.25
Grade (per cent):								
1	0.38	0.51	0.63	0.71	0.79	0.87	0.95	1.03
2	1.01	1.35	1.69	1.90	2.11	2.32	2.53	2.75
3	1.65	2.20	2.75	3.09	3.43	3.78	4.12	4.46
4	2.28	3.04	3.80	4.28	4.75	5.23	5.70	6.18

[a] This table is, in part, due to F. K. Vial, consulting engineer, Association of Manufacturers of Chilled Car Wheels.

[b] An allowance of 8 pounds per ton has been made for train resistance.

It is apparent from the above table that 630 000 foot-pounds of energy are destroyed per minute by the brake on each wheel of a 100 000-pound car in maintaining a constant velocity under the following operating conditions: Descending a 1 per cent grade at 1 mile per minute, or 60 miles per hour; 2 per cent grade at 1 mile per 2.68 minutes, or 22 miles per hour; 3 per cent grade at

1 mile per 4.37 minutes, or 13 miles per hour; 4 per cent grade at 1 mile per 6.03 minutes, or 10 miles per hour.

However, the actual test conditions were more severe than these figures indicate on account of the difference in the heat dissipation in the two cases. In these tests the resistor completely encircled the wheel and was thermally insulated to drive the heat into the wheel. Under these conditions a larger percentage of the energy supplied to the resistor entered the wheel than would be the case when the same wheel is subjected to brake application, as occurs in service, due to the fact that part of the energy destroyed by friction between the shoe and wheel goes to heating the brake shoe, and thence by radiation to the air, and, further, the shoe only bears on a small part of the circumference, thus allowing the heat in the uncovered part of the tread to radiate directly into the air instead of entering the wheel.

In the Bureau tests the treads of the lightest wheels reached a temperature of 380° C (716° F) in about 75 minutes, while it required from 100 to 105 minutes for the heaviest wheels to reach the same temperature. Readings were taken of the temperature, strain, and power input at regular intervals, a strain gage reading of the cold wheel being also taken before the test was started. When the desired tread temperature was reached, the power was shut off and the asbestos covering on the resistor was removed to permit more rapid dissipation of the heat. Temperature and strain gage readings were also taken during cooling and after the wheel was at room temperature.

The elongation as determined by the strain gage is attributable to two causes: (1) An elongation due to the thermal expansion of metal, and (2) elongation caused by the strain due to the temperature gradient from tread to hub of the wheel. By knowing the coefficient of expansion and the temperature rise it was possible to calculate the thermal expansion. By deducting the elongation due to this expansion from the total elongation the elongation due to stress alone was determined. The relation between stress and strain on samples actually taken from the wheels made it possible to convert the strain readings into stress values.

2. AUXILIARY TESTS

It was necessary to make a number of auxiliary tests to supplement and interpret the results of the special thermal tests made at the Bureau of Standards. These tests consisted of determina-

tion of the coefficient of expansion, stress-strain curves, chemical analyses, and metallographic examination.

(*a*) LINEAR THERMAL EXPANSION.—The coefficient of expansion from the range 20 to 310° C was determined on specimens cut from one of the wheels furnished by each of the three manufacturers. The samples were 31 centimeters in length and 1 centimeter square.[4]

The iron from A showed a unit expansion represented by the equation $\frac{\Delta l}{l} = 10.47 \times 10^{-6}t + 7.51 \times 10^{-9}t^2$, where t is the temperature rise in degrees centigrade and will apply for temperatures between 0 and 300° C. For manufacturers B and C the equations are, respectively, $\frac{\Delta l}{l} = 10.76 \times 10^{-6}t + 6.86 \times 10^{-9}t^2$ and $\frac{\Delta l}{l} = 10.62 \times 10^{-6}t + 7.34 \times 10^{-9}t^2$. The above equations were obtained by the method of least squares, and by the same manner a composite equation was computed which would apply to all three products. The composite equation is $\frac{\Delta l}{l} = 10.60 \times 10^{-6}t + 7.30 \times 10^{-9}t^2$. Although the coefficients in these equations appear somewhat different, the table below shows that the unit expansion as calculated from the separate equations agrees well within the precision required, as shown later, and the use of the composite equation is justified.

TABLE 6.—Comparison of Expansion Equations

Temperature rise (° C)	Total expansion, in inches per inch calculated by equations, for iron from manufacturer—			
	A	B	C	Composite
50	0.00054	0.00056	0.00055	0.00055
100	.00112	.00115	.00114	.00113
150	.00174	.00177	.00176	.00175
200	.00239	.00243	.00242	.00241
250	.00309	.00312	.00311	.00311
300	.00382	.00385	.00385	.00384

(*b*) MECHANICAL PROPERTIES.[5]—The mechanical properties of the material were determined on specimens of 8-inch gage length taken from the plates of the wheels which had not cracked after the thermal stress tests had been completed. The samples were cut from a chord of the wheel or in a direction principally normal

[4] The method used for the determination of expansion is described in B. S. Sci. Papers, No. 352, p. 390. These determinations were made in the expansion laboratory under the direction of Dr. W. H. Souder.

[5] These tests were made in the engineering materials section under the direction of H. L. Whittemore.

to the radial stresses developed by the thermal tests. Preliminary runs on other wheels in which strain measurements were also taken circumferentially as well as radially had shown the circumferential stresses to be practically negligible, so that specimens taken from the wheel as above described can be considered as not having been previously strained, and the stress-strain data obtained in the tensile test would not be affected by heatings of the wheel. Preliminary data were also obtained on the tensile properties of cast iron at temperatures up to 350° C which gave results similar to those at room temperature.

Several specimens were taken from two wheels of each manufacturer in order to obtain a fair average of the wheels from each foundry. For the purpose of computing the stress values in the heated wheels the modulus of elasticity is required, but since cast iron has no such constant modulus when tested in tension the stress-strain curve was determined up to as near rupture as possible and then extrapolated to rupture by the data obtained for the elongation and ultimate strength. Such curves, each the mean of all tests on iron from a given manufacturer, are shown in Fig. 17. A 230 000-pound Emery testing machine and an Ewing extensometer were used in the tests.

TABLE 7.—Average Results of Tensile Tests

Manufacturer	Apparent elastic limit	Ultimate strength	Elongation in 8 inches	Reduction of area	Modulus of elasticity at "zero stress"
	Lbs./in.²	Lbs./in.²	Per cent	Per cent	Lbs./in.²
A	9 600	26 700	0.8	0.3	17 300 000
B	6 300	18 900	.8	.4	15 400 000
C	11 000	27 000	.8	.4	18 400 000

In Table 7 are shown the average results for the tensile tests. Here the modulus of elasticity for "zero stress" is given, this value being the slope of the stress-strain curve at the origin. The "apparent elastic limit" [6] was also determined rather than the proportional limit. The iron from the wheels of manufacturer C showed the highest apparent elastic limit, ultimate strength, and modulus of elasticity, while that from manufacturer A was next, and the B iron gave values considerably lower.

[6] "The apparent elastic limit is the point on the stress-strain diagram of any material in any kind of test at which the rate of deformation is 50 per cent greater than it is at the origin"—Materials of construction, Johnson, 1st ed., p. 19.

(*c*) CHEMICAL COMPOSITION.—The chemical composition of the 28 wheels tested at the Bureau of Standards was determined.[7] The samples were obtained by drilling completely through the plate of the wheel about midway between hub and tread. The results of the analyses are shown in Table 8.

TABLE 8.—Chemical Composition of Wheels Tested at Bureau of Standards

Wheel number	Manufacturer	Carbon			Manganese	Phosphorus	Sulphur	Silicon
		Total	Graphitic	Combined				
		Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1	A	3.33	2.79	0.54	0.61	0.40	0.144	0.59
2	A	3.40	2.75	.65	.57	.41	.137	.58
3	A	3.39	2.82	.57	.57	.39	.140	.62
4	A	3.37	2.73	.64	.57	.40	.141	.62
5	A	3.25	2.81	.44	.55	.38	.138	.61
6	A	3.41	2.64	.77	.52	.40	.140	.59
Average	A	3.36	2.76	.60	.57	.40	.140	.60
Maximum	A	3.41	2.82	.77	.61	.41	.144	.62
Minimum	A	3.25	2.64	.44	.52	.38	.137	.58
7	B	3.36	2.85	.51	.77	.33	.126	.56
8	B	3.69	3.00	.69	.74	.32	.113	.60
9	B	3.66	3.01	.65	.74	.33	.125	.57
10	B	3.57	3.01	.56	.73	.33	.110	.55
11	B	3.59	2.94	.65	.73	.33	.109	.54
12	B	3.70	3.01	.69	.75	.33	.114	.65
13	B	3.46	3.06	.40	.75	.33	.116	.59
14	B	3.41	3.10	.31	.72	.34	.118	.58
Average	B	3.56	3.00	.56	.74	.33	.116	.58
Maximum	B	3.70	3.06	.69	.77	.34	.126	.65
Minimum	B	3.36	2.85	.31	.72	.32	.109	.54
15	C	3.27	2.56	.71	.65	.31	.176	.62
16	C	3.26	2.56	.70	.64	.30	.172	.80
17	C	3.25	2.56	.69	.60	.31	.185	.60
18	C	3.14	2.63	.51	.63	.31	.181	.56
19	C	3.20	2.70	.50	.80	.30	.158	.57
20	C	3.18	2.56	.62	.79	.29	.160	.64
21	C	3.26	2.60	.66	.77	.30	.167	.60
22	C	3.29	2.62	.67	.74	.29	.172	.87
23	C	3.23	2.79	.44	.71	.28	.164	.67
24	C	3.29	2.62	.67	.67	.28	.166	.80
25	C	3.19	2.60	.59	.64	.28	.169	.67
26	C	3.27	2.80	.47	.65	.28	.172	.70
27	C	3.22	2.49	.73	.68	.28	.185	.80
28	C	3.14	2.54	.60	.76	.28	.173	.65
Average	C	3.23	2.62	.61	.70	.29	.172	.68
Maximum	C	3.29	2.80	.73	.80	.31	.185	.87
Minimum	C	3.14	2.49	.44	.60	.28	.158	.56

The ranges of the various elements in the 28 test wheels are as follows:

	Per cent
Total carbon	3.14 –3.70
Graphitic carbon	2.49 –3.06
Combined carbon	0.31 –0.77
Manganese	0.52 –0.77
Silicon	0.54 –0.87
Phosphorus	0.28 –0.41
Sulfur	0.109–0.185

[7] These analyses were made under the direction of H. A. Bright.

Since the wheels which were tested at the place of manufacture were supposed to be representative of the wheels tested at the Bureau of Standards, and since the former passed the requirements of the American Railway Association specifications, it seems safe to say that apparently satisfactory wheels may be made in which the composition covers the ranges given. It may be stated, further, that by proper control of manufacturing conditions, such as molding, pouring, annealing, etc., the ranges given above can no doubt be enlarged upon.

These statements, however, should not be construed to mean that it is necessary to confine the various elements within the above ranges, because chemical composition is only one of the factors that assist in the production of good wheels. Although the chemical composition of the wheels is of interest, it is thought to be undesirable to attempt to correlate so few compositions in terms of the behavior of the wheels in view of the great chemical complexity of car-wheel mixture and on account of varying mechanical properties from apparently similar composition. It would be highly desirable to later secure additional and adequate information on the questions of composition and foundry mixtures particularly with respect to the manganese-sulphur ratio, combined carbon, and phosphorus.

(*d*) METALLOGRAPHIC EXAMINATION.[8]—The three specimens used for micrographic examination were cut from the ends of the bars taken from the wheels for tensile tests, one from each manufacturer. The material was examined as follows: First, the polished but unetched specimen, to show the distribution of graphitic plates and the size and distribution of the inclusions; second, the polished and heat-tinted specimen, to show the distribution and relative amount of phosphide eutectic and also to identify the sulphide inclusions; and, thirdly, the etched specimens, to show the nature of the matrix, which comprises the body of the iron. The micrographs, nine in number, are shown in Figs. 18 to 20, inclusive. A careful examination of these micrographs will show differences in the structure. For instance, the iron from foundry B seems to contain long, thin, intermingling graphite flakes, while the iron from the other two manufacturers contains shorter and thicker flakes. Differences in the amount of sulphides and phosphides from the different foundries are also apparent. For reasons similar to those given under chemical composition no

[8] This examination was made by S. Epstein.

attempt is made to correlate these micrographs with the test results on the wheels.

3. ACCURACY OF STRESS MEASUREMENT

The measured elongation is due to two effects—thermal expansion and stress—and may be represented by the equation $e = \Delta l + \Delta s$. Δl is represented approximately by the formula $\frac{\Delta l}{l} = 10.6t \times 10^{-6}$, where t is the temperature rise. The coefficient of t may have a possible error of one-half per cent, and the temperature measurements are good to 5° C. For a temperature rise of 100° C, then

$$\frac{\Delta l}{l} = \left\{10.6\ (1 \pm 0.005)\right\}\left\{100(1 \pm 0.05)\right\} \times 10^{-6}$$
$$= 1060\ (1 \pm 0.005 \pm 0.05) \times 10^{-6}$$
$$= 0.0011 \pm 0.0001 \text{ inch per inch.}$$

A 2-inch Berry strain gage when rigidly fastened to a test bar will admit of estimations being made to 0.00001 of an inch; but in this work, where the strain gage was held in the hand and constantly changed from various gage marks, it was impossible to estimate as closely as above, and the readings of e may be considered as having a possible error of ± 0.0001 of an inch. Then $(e \pm 0.0001) = (\Delta l \pm 0.0001) + \Delta s$ or Δs will have a probable error ± 0.0002 inch per inch.

By comparison with Fig. 17 it will be seen that this error in strain corresponds to an error in stress of ± 4000 pounds per square inch for low values of stress, but for higher values would be considerably less, or about 400 pounds per square inch. The error in determining the stress-strain curves for the tensile specimens is negligible for small strains in comparison with the strain measurements on the wheels. In the upper region of the curves, however, the error is of about the same magnitude as the wheel-strain error, such that it is a fair assumption that the probable error throughout the major range of the stress measurements is ± 3000 pounds per square inch.

4. RESULTS OF THERMAL STRESS TESTS

(*a*) STRESSES.—It was found in the tests that an unexpectedly large number of the wheels developed cracks in the plates. These cracks were circumferential in nature and were all approximately at the same distance from the center of the wheel, namely, 9

inches. Of the 28 wheels 16, or 57 per cent, developed cracks in the plates. Some of the cracks were barely perceptible to the unaided eye even at the time that the maximum temperature gradient between tread and hub existed and were of very short length, while others developed comparatively early in the test and almost completely encircled the wheel. These larger cracks opened up to about one-sixteenth of an inch and were, of course, readily apparent. In Figs. 21 to 23, inclusive, are given typical examples of the cracked wheels. The cracks themselves were marked with white chalk in order to make their location easily visible in the photographs.

For the 28 wheels which were used for thermal stress tests at the Bureau computations were made which showed the stresses existing in the wheels at each of the strain-gage positions at intervals of 10 minutes on heating and for longer intervals of time during cooling of the wheel. The magnitude of these stresses is shown in Figs. 1 to 14, where they are plotted against their relative positions along the radius of the wheel. These curves indicate the stresses existing in the wheel at the time of failure of the wheel by cracking or in the event the wheel did not crack at the time the maximum temperature gradient existed between tread and hub. The temperature distribution at the same time is also shown in a similar manner. As all the wheels were tested in duplicate, both curves of each design of wheel were plotted together. Thus, in Fig. 1, the stress distribution curves of wheels 1 and 2 are given. The arrows on the drawing show the approximate location of the cracks, if any occurred.

Figs. 1 to 3, inclusive, show the curves of the 6 wheels submitted by manufacturer A. Wheels 3 and 4 developed slight cracks, while the remaining 4 wheels showed no evidence of failure.

Figs. 4 to 7, inclusive, show the curves of the 8 wheels submitted by manufacturer B, numbers 7 to 14, inclusive. The maximum stresses in the wheels submitted by this manufacturer are considerably lower than those in the wheels submitted by either manufacturer A or C. Three of the 8 wheels, numbers 7, 8, and 10, developed cracks in the tests.

The stress curves of wheels 15 to 28, inclusive, furnished by manufacturer C, are shown in Figs. 8 to 14, inclusive. With the exception of Fig. 12, the stress distribution is of the same general character as in the other wheels tested. In the single-plate wheel, as shown in Fig. 12, the stress distribution is decidedly

different than it is in the other types. The single-plate type of wheel is a special experimental design and is not used by any railroad. It was thought that this type of wheel might show greater ability to withstand operating conditions. It is apparent from Fig. 12 that the metal is in compression near the rim on the outside of the wheel. In order to have the stresses in equilibrium, there must necessarily be tensile stresses near the rim on the opposite or inside of the wheel. No measurements were made to determine the stresses on the inside. It will be noticed further from the same figure that the maximum tensile stress occurs on the large radius on the outer face near the hub of the wheel. Although this wheel showed higher strains and hence stresses for a given heat input than the M. C. B. and arch-plate types, yet the distribution is such that when subjected to additional stress-producing factors, such as mounting, static load, and flange pressure, it seems probable that the strain or stress under those conditions would be less than in either the M. C. B. or arch-plate designs. For instance, the compression found near the rim on the outer face through heat application may be increased slightly when the static load is added, but the addition of the flange pressure or side thrust would more than offset this addition, so that the net effect would be a reduction in the strains or stresses found. The tension unquestionably present on the inner face near the rim would similarly be reduced. Further, the magnitude of the tensile strains or stresses found in the hub region would be counteracted by compression resulting from mounting the wheel onto its axle. Both of the wheels of this type withstood the thermal and drop tests as required by the M. C. B. specifications. In view of these facts the results indicate that the single-plate design, although it does not withstand the special thermal test made by the Bureau as well as the M. C. B. and arch-plate types, yet it may possibly be better adapted to service conditions.

The highest maximum stress measured was 28 400 pounds per square inch, while the lowest stress at which failure occurred was 14 000 pounds per square inch. It is possible that the latter wheel, No. 18, had an internal flaw which accelerated the failure. The maximum stresses observed are in nearly all cases very close to the ultimate strength of the cast iron of which the wheel is composed. Thus, for manufacturer C the stresses are in the neighborhood of 26 000 pounds per square inch, and this material

was shown to have a tensile strength of 27 000 pounds per square inch. The wheels from foundry B usually showed stresses around 17 000 pounds per square inch, while the tensile strength was about 19 000 pounds per square inch.

(*b*) TEMPERATURES.—The curves for temperature distribution are all of the same general character, showing the highest temperature at the tread and gradually falling off toward the center. The data from which these curves are plotted are given in Table 9, which gives the temperatures along the vertical axis, as indicated by the thermocouples 1 to 7, inclusive, at the time of failure or maximum temperatures in the event that the wheel did not fail.

TABLE 9.—Temperature Distribution in Wheels Due to Heating Tread

Wheel number	Foundry	Cracked or not	Temperature at failure or maximum for seven radial positions						
			1	2	3	4	5	6	7
			°C	°C	°C	°C	°C	°C	°C
1	A	No	355	310	241	189	155	130	107
2	A	No	348	319	240	189	171	132	104
3	A	Yes	308	242	194	158	136	108	92
4	A	Yes	334	299	247	193	147	135	89
5	A	No	358	314	245	191	153	126	98
6	A	No	355	311	245	193	169	145	117
7	B	Yes	314	297	225	171	155	128	87
8	B	Yes	225	208	164	130	114	85	71
9	B	No	352	323	259	206	173	135	104
10	B	Yes	323	312	251	192	167	134	110
11	B	No	360	325	258	210	183	153	135
12	B	No	352	319	263	227	189	175	145
13	B	No	361	328	263	227	206	185	153
14	B	No	343	319	270	221	179	143	119
15	C	Yes	260	237	176	130	102	77	17
16	C	Yes	215	179	139	107	75	58	44
17	C	Yes	243	207	151	108	79	64	52
18	C	Yes	174	138	95	67	53	42	31
19	C	Yes	250	216	174	165	132	92	69
20	C	Yes	303	.....	211	147	111	85	70
21	C	Yes	310	285	223	175	159	111	96
22	C	Yes	285	242	189	165	129	94	79
23	C	No	386	349	299	228	185	132	121
24	C	Yes	358	337	279	210	171	112	116
25	C	No	356	317	254	208	169	157	128
26	C	Yes	303	268	212	172	161	118	101
27	C	Yes	311	286	221	190	150	128	86
28	C	No	349	302	247	187	159	147	109

A typical curve showing the manner in which the temperatures build up with time at different positions in the wheel is given in Fig. 24 for the 700-pound arch-plate wheel No. 3. Couple No. 1, which was nearest the tread, attained a maximum temperature of 344° C (651° F) after 95 minutes, and couple No. 7, which was nearest the hub, indicated a temperature of 147° C (297° F). This wheel, however, cracked 65 minutes after the start of the test, at which time the temperatures were 279° C (554° F) and

91° C (196° F) for couples Nos. 1 and 7, respectively. It is evident that these temperature gradients were sufficient to develop stresses in the plate of the wheel reaching the ultimate strength of the iron.

TABLE 10.—Condition of Wheels at End of Heating Period or at Time of Cracking

Type of wheel	Wheel number	Approximate circumferential length of crack in degrees	Length of test in minutes	Total energy to resistor in millions foot-pounds	Temperature of couple No. 1 (nearest tread)		Temperature difference between couples Nos. 1 and 7		Maximum stress in pounds per square inch	
									Estimated amount	In gage line
					° C	° F	° C	° F		
625-pound M. C. B.	1	None	83	55.0	355	671	248	478	27 600	D
	2	None	86	57.6	348	658	244	471	23 300	I
	15	145	50	30.7	260	500	243	469	25 900	I
	16	340	42	24.9	215	419	171	340	24 700	E
625-pound arch plate	7	190	64	40.8	314	597	227	441	20 200	J
	8	220	49	29.8	225	437	154	309	19 900	D
650-pound arch plate	17	120	43	25.6	243	469	191	376	26 700	J
	18	350	33	19.0	174	345	143	289	14 000	E
700-pound arch plate	3	35	65	41.3	308	586	216	421	23 300	D
	4	75	75	49.0	334	633	245	473	24 500	E
	9	None	95	64.5	352	666	248	478	17 400	D
	10	15	80	53.0	323	613	213	415	17 100	E
	19	130	53	32.9	250	482	181	358	26 000	J
	20	130	68	43.7	303	577	263	505	26 500	E
725-pound M. C. B.	5	None	85	56.7	358	676	260	500	24 800	H
	6	None	87	58.2	355	671	238	460	23 800	C
	21	120	75	49.0	310	590	214	417	26 400	D
	22	210	60	37.8	285	545	206	403	26 900	I
750-pound single plate	23	None	90	60.9	386	727	265	509	26 900	J
	24	10	80	53.0	358	676	242	468	28 400	J
775-pound arch plate	11	None	97	66.1	360	680	225	437	16 800	I
	12	None	104	71.5	352	666	207	405	17 100	J
	25	None	79	52.0	356	673	228	442	23 500	.....
	26	40	79	52.0	303	577	202	396	24 800	I
850-pound arch plate	13	None	112	78.5	361	682	208	406	17 700	I
	14	None	94	63.7	343	649	224	435	18 300	E
	27	10	82	54.4	311	592	225	437	23 400	D
	28	None	97	66.1	349	660	240	464	24 800	D

Table 10 classifies the wheels in the order of the temperature of the tread at the time of failure or at the maximum temperature in case cracking did not occur. There is also given the circular length of the crack in degrees, the time at which this crack occurred, energy supplied to the wheel by the electric heater, and the maximum stress resulting from this energy. It will be noticed that those wheels which failed comparatively early with low values of applied energy had very long cracks, sometimes nearly encircling

the wheel; also, as would be expected, the lighter-weight wheels fail with smaller application of energy than the heavier wheels.

In Table 11 is given the average temperature rise in one hour in the parts of the wheels indicated.

TABLE 11.—Temperature Distribution in Wheels Due to Heating Tread

Wheel weight (pounds)	Temperature gradient at the end of one hour in degrees centigrade for thermocouple positions—							Temperature differences between 1–7
	1	2	3	4	5	6	7	
625	283	254	198	149	125	99	75	208
700	278	244	196	156	126	102	79	199
775	263	232	181	146	119	99	81	182
850	252	225	178	142	112	90	73	179

It would appear from Table 11 that for a given heat input the rate at which the wheel becomes heated is slightly retarded as the weight of the wheel increases. The difference in temperature indicated above decreases at an average rate of 10 degrees for each additional 75 pounds of metal. This shows that the heavier wheels have lesser gradients at the end of a given heating period and suggest also lesser strains and stresses.

(*c*) Relation of Weight to Strain.—To show the relative ability of different weights of the arch-plate type wheel to withstand the effects of temperature gradients, Table 12 was made.

In it are given the unit strains due to internal stress 40 minutes after the start of the tests. The unit strains at that time were averaged as shown for each of the types tested. Then, by using the average unit strain as found in the 625-pound M. C. B. type of wheel as a basis for comparison, the relative average strains at the end of 40 minutes of heating are given in the table. It is evident that the 850-pound M. C. B. (arch plate) was best able, while the 750-pound single plate was least able to withstand the special Bureau thermal test. In the case of the single-plate wheel this does not necessarily indicate that this type would be least satisfactory in service, as was indicated above. By plotting the average unit strain against the weight of wheel (Fig. 26) for the arch-plate pattern the effect of the additional weight becomes apparent. Since only two 625-pound and two 650-pound arch-plate wheels were tested and each of these types were furnished by different foundries, the averages given for them should be given less weight than the remaining three weights, namely, 700,

TABLE 12.—Maximum Strains (in Inches) Recorded After 40 Minutes of Heating

Type of wheel	Wheel numbers	Gage lines	Strains in wheels submitted by manufacturers—			Average maximum strain	Relative average strain
			A	B	C		
625-pound M. C. B.	1, 2, 15, 16	Vertical	0.0030	.....	0.0032	0.0030	100
			.0018	.....	.0038		
		Horizontal	.0021	.....	.0040		
					.0033		
625-pound arch plate	7, 8	Vertical	.....	0.0027		.....	.0030	100
				.0029			
		Horizontal	.....	.0035			
				.0031			
650-pound arch plate	17, 18	Vertical	.....	.....	.0028	.0034	113
		Horizontal	.....	.....	.0041		
700-pound arch plate	3, 4, 9, 10, 19, 20	Vertical	.0021	.0024	.0017	.0024	80
			.0025	.0020	.0042		
		Horizontal	.0016	.0023	.0026		
					.0030		
725-pound M. C. B.	5, 6, 21, 22	Vertical	.0023	.....	.0026	.0027	90
			.0018	.....	.0034		
		Horizontal	.0025	.....	.0029		
			.0025	.....	.0034		
750-pound single plate	23, 24	Vertical	.....	.....	.0030	.0035	117
					.0035		
		Horizontal	.....	.....	.0034		
					.0040		
775-pound arch plate	11, 12, 25, 26	Vertical	.....	.0014	.0022	.0020	57
				.0015	.0022		
		Horizontal	.....	.0018	.0026		
				.0018	.0025		
850-pound arch plate	13, 14, 27, 28	Vertical	.....	.0017	.0016	.0018	60
				.0020	.0019		
		Horizontal	.....	.0018	.....		
				.0017	.0020		

775, and 850 pounds. It is felt that the curve as shown gives a fair approximation of the effect of additional metal in withstanding the effect of thermal gradients. Taken from the curve their relative strains are as follows:

Arch plate type	Relative strain
625-pound	100
650-pound	86
700-pound	69
775-pound	57
850-pound	51

The curve indicates further that a certain amount of metal does more good when added to the lighter weight than it does when added to the heavier weight wheels. In addition, it will be noticed that at 850 pounds the curve is rapidly approaching the horizontal. This indicates that if the weight were still further in-

creased a weight would be reached at which additional metal would have little effect toward enabling the wheel to withstand brake application.

V. SUMMARY AND CONCLUSION

A method has been described for electrically heating car wheels in the laboratory which produce effects similar to that encountered through long application of the brakes on heavy grades. Observations have been made of the strains resulting from such heating on wheels of various design and weight from three different manufacturers. The rate of heating was severe enough to crack many of the wheels, and the internal stresses in all cases approximated the ultimate tensile strength as shown by test specimens. The total number of wheels tested is too small to draw any definite conclusions, but the results seem to point to the following generalities, which should be confirmed by a greater number of tests:

1. The method used was such that the heat input to the wheel was much greater than that which would enter a wheel doing its proportionate part in taking any car down any grade found on trunk-line railroads at a reasonable speed.

2. The rate of heating in the special thermal test as conducted by the Bureau were more severe than actual service conditions, so that wheels which stand up under the foregoing tests will not fail under the extreme conditions of a long and heavy application of the brakes. These special thermal tests, however, are not as severe as the thermal test required by the M. C. B. specifications, in which for rejection a wheel must crack through the rim in two minutes. In the tests here reported no wheels cracked through the rims, although a large number developed cracks in the plates.

3. The maximum stresses developed are very close to the tensile strength of the cast iron and are some function of the strength of the iron.

4. Preliminary tests (not recorded herein) show that the stress in a tangential direction on the outer face and also the stress in both the radial and tangential direction on the bracket side of the wheel are relatively small when compared to those in a radial direction on the outer face of the wheel.

5. The maximum tensile stresses occur in a radial direction near the junction of the double plates in the M. C. B. or Washburn type of wheel. In the arch-plate type the maximum stress is somewhat nearer the hub. This seems a desirable condition in

that it then lies in the region where it is counteracted by the strains due to forcing the wheel onto its axle.

6. The tests also lead one to believe that the operating conditions to which wheels are subjected may be as important a factor in the safety of the wheel as are the problems arising in their manufacture.

7. By proper distribution of metal in the single-plate type of wheel there would appear to be a possibility of securing a wheel more capable of meeting service requirements.

8. With identical rates of heat input the heavier-weight wheels withstand the effect of tread heating with less strain than the lighter wheels. It seems conceivable, however, that a wheel may be made where increased weight will not aid the wheel to withstand brake application. Such weight, however, is beyond the weights in use to-day.

It is expected to publish shortly the results of similar tests on typical steel wheels, and it is considered desirable to continue work on chilled-iron wheels to answer some of the outstanding questions as to their behavior as related to design, composition, and manufacture.

The authors desire to acknowledge the assistance given by several members of the Bureau throughout the investigation. The method used was largely suggested by Dr. P. D. Merica, who had immediate charge of the investigation at its inception. He was succeeded by C. H. Strand, under whose direction many of the data were obtained. A. S. McCabe, A. L. Hamilton, and E. Q. Martin assisted in making the necessary measurements on the wheels; G. W. Quick and S. J. Rosenberg aided in the calculations. We are also glad to record the cooperation of those manufacturers who so generously furnished the wheels and otherwise gave assistance, and especially F. K. Vial, consulting engineer of the Association of Manufacturers of Chilled Car Wheels.

WASHINGTON, February 21, 1921.

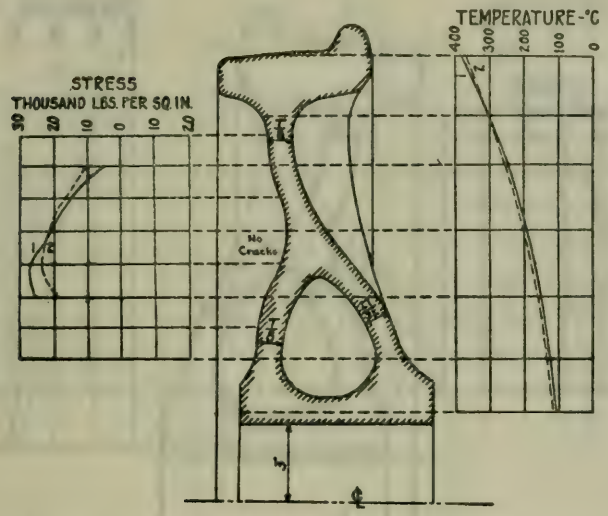


FIG. 1.—*Cross section and stress and temperature gradients for wheels 1 and 2—625-pound M. C. B. type*

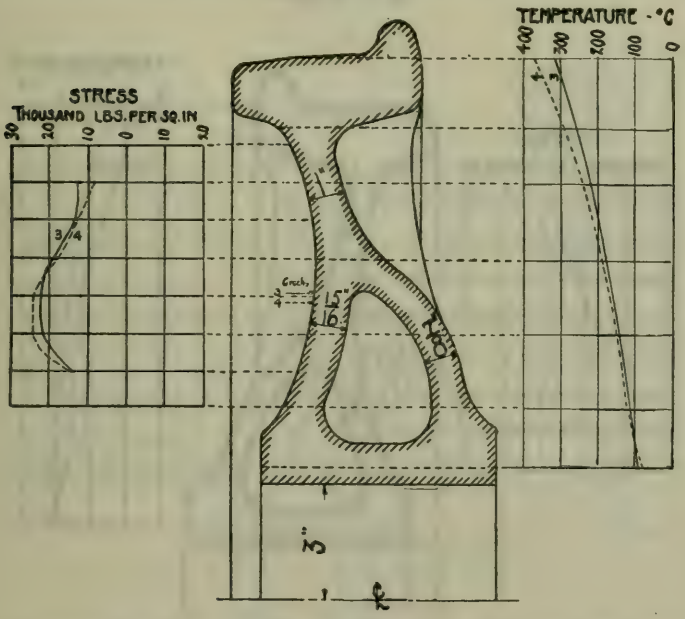


FIG. 2.—*Cross section and stress and temperature gradients for wheels 3 and 4—700-pound arch-plate type*

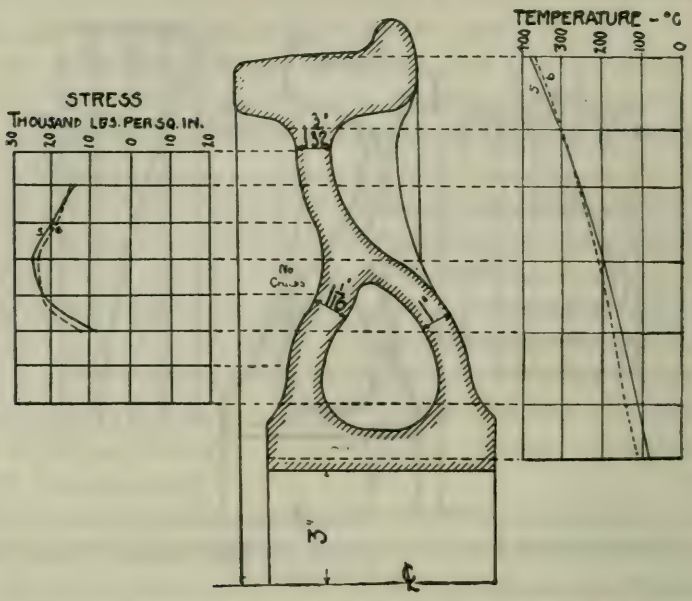


FIG. 3.—*Cross section and stress and temperature gradients for wheels 5 and 6—725-pound M. C. B. type*

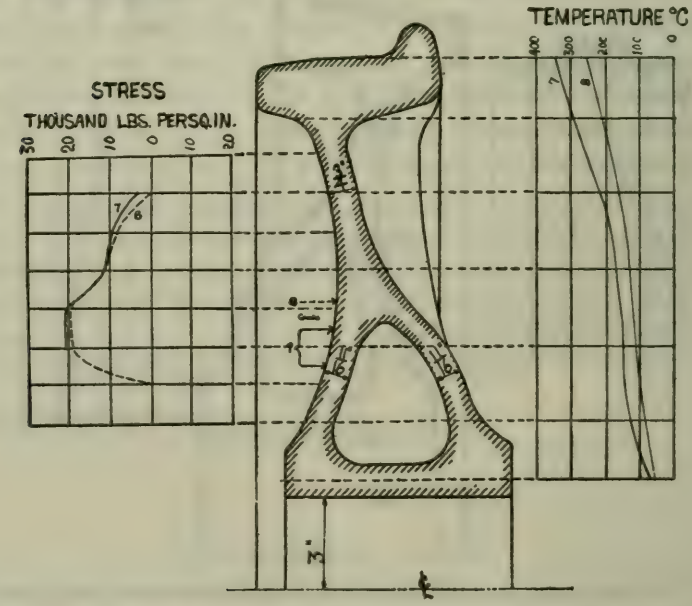


FIG. 4.—*Cross section and stress and temperature gradients for wheels 7 and 8—625-pound arch-plate type*

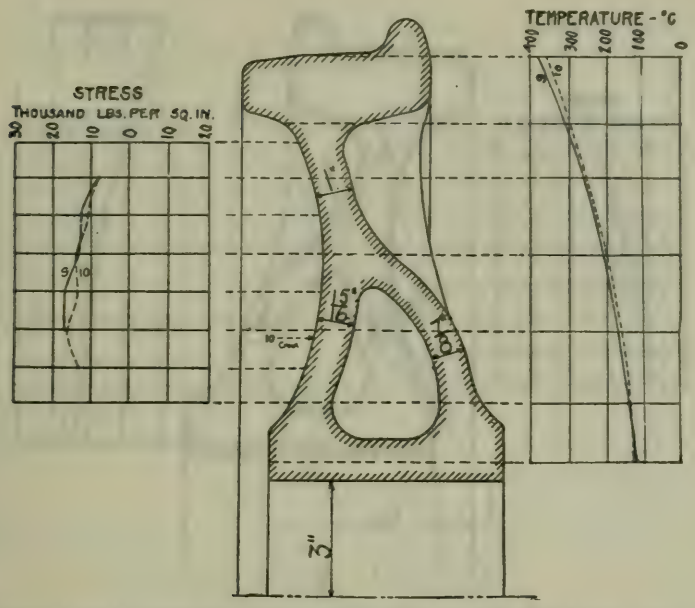


FIG. 5.—*Cross section and stress and temperature gradients for wheels 9 and 10—700-pound arch-plate type*

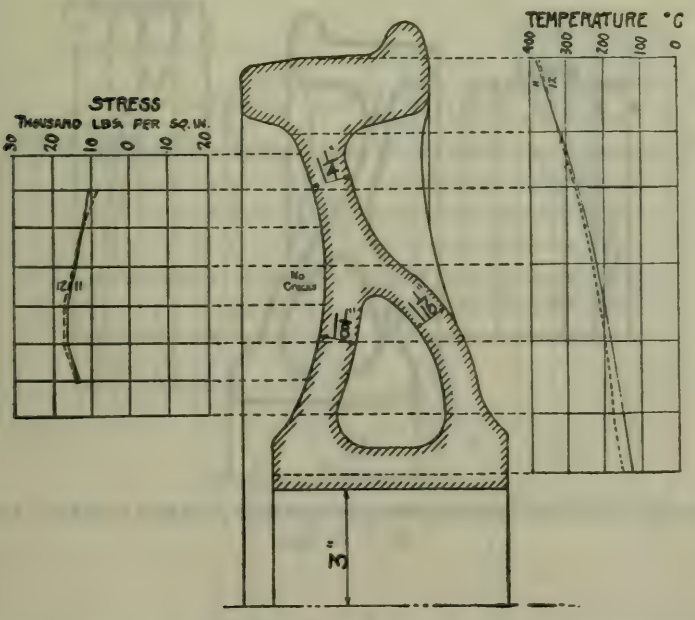


FIG. 6.—*Cross section and stress and temperature gradients for wheels 11 and 12—775-pound arch-plate type*

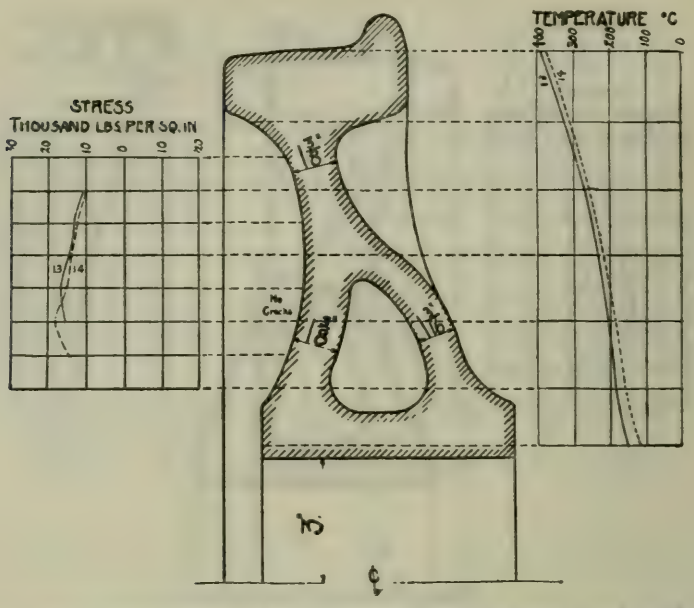


FIG. 7.—*Cross section and stress and temperature gradients for wheels 13 and 14—850-pound arch-plate type*

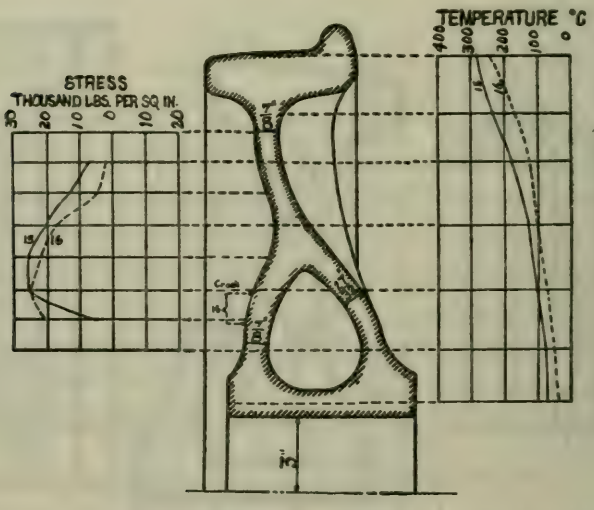


FIG. 8.—*Cross section and stress and temperature gradients for wheels 15 and 16—625-pound M. C. B. type*

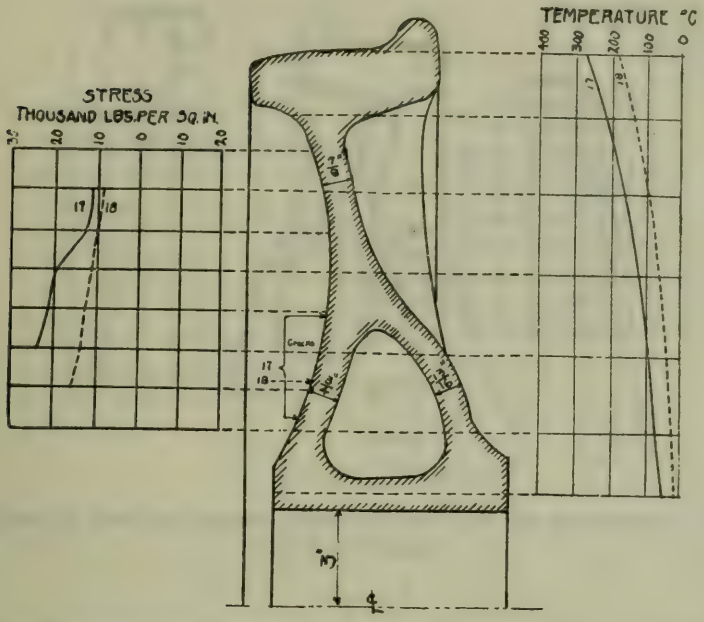


FIG. 9.—*Cross section and stress and temperature gradients for wheels 17 and 18—650-pound arch-plate type*

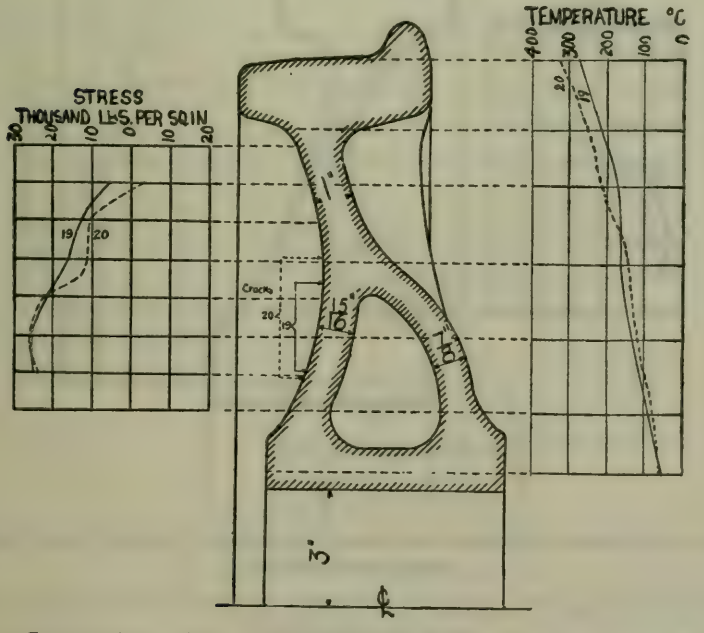


FIG. 10.—*Cross section and stress and temperature gradients for wheels 19 and 20—700-pound arch-plate type.*

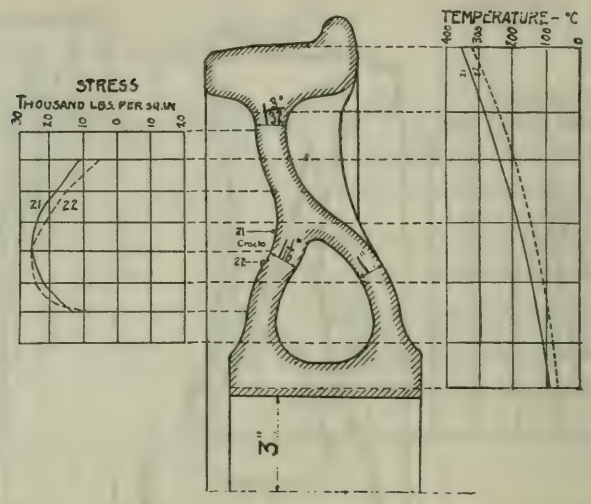


FIG. 11.—*Cross section and stress and temperature gradients for wheels 21 and 22—725-pound M. C. B type*

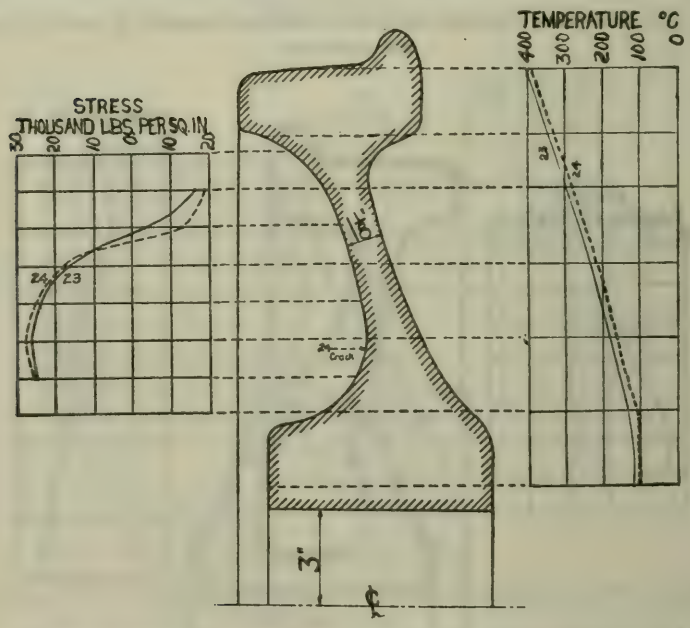


FIG. 12.—*Cross section and stress and temperature gradients for wheels 23 and 24—750-pound single-plate type*

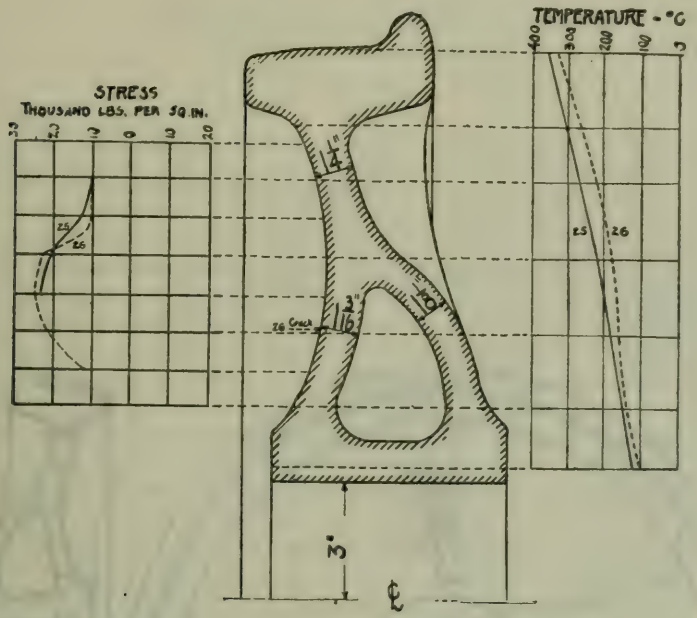


FIG. 13.—*Cross section and stress and temperature gradients for wheels 25 and 26—775-pound arch-plate type*

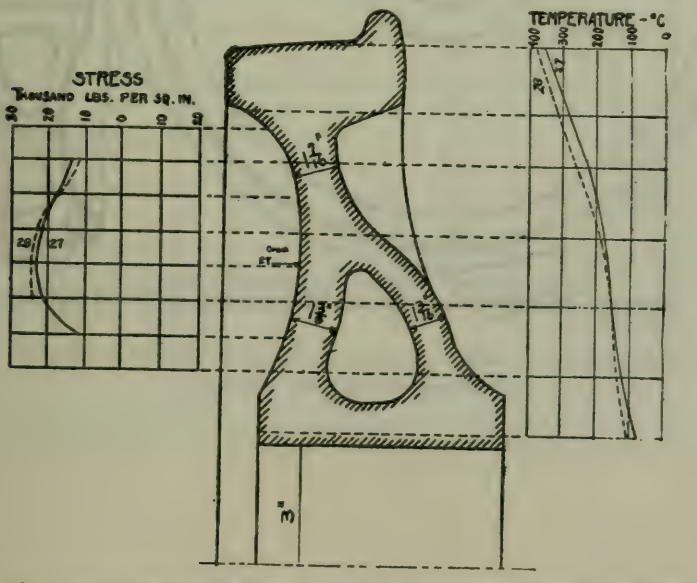


FIG. 14.—*Cross section and stress and temperature gradients for wheels 27 and 28—850-pound arch-plate type*

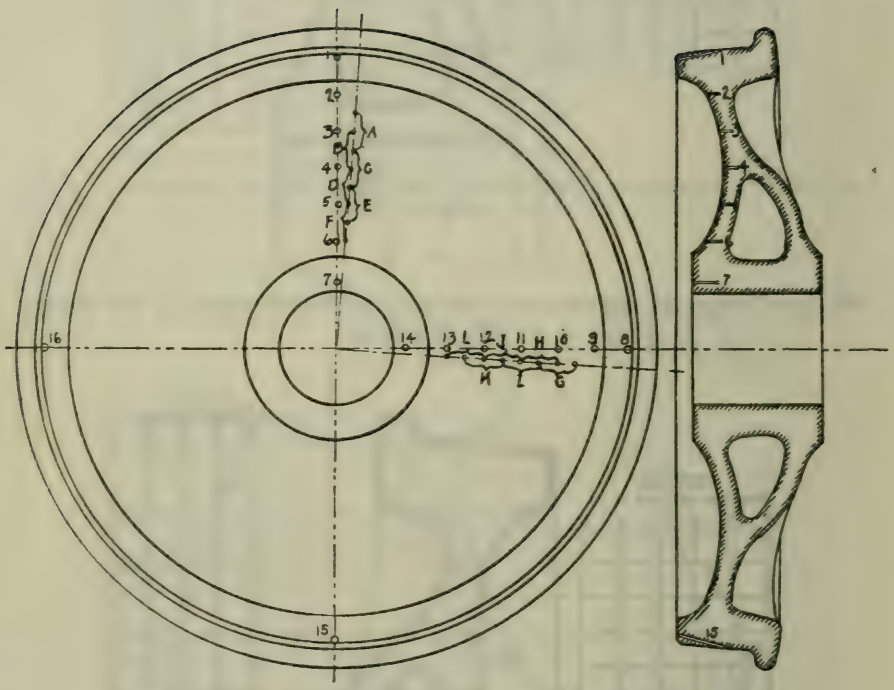


FIG. 16.—*Sketch showing location of thermocouple and strain-gage holes*

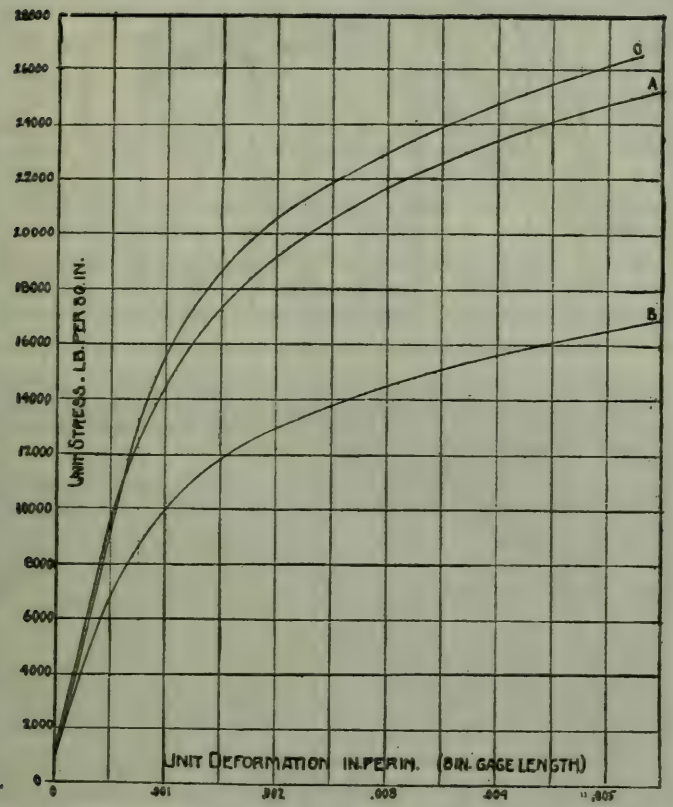


FIG. 17.—*Composite stress-strain curves obtained from tensile test on samples of cast iron from wheels of the three manufacturers*

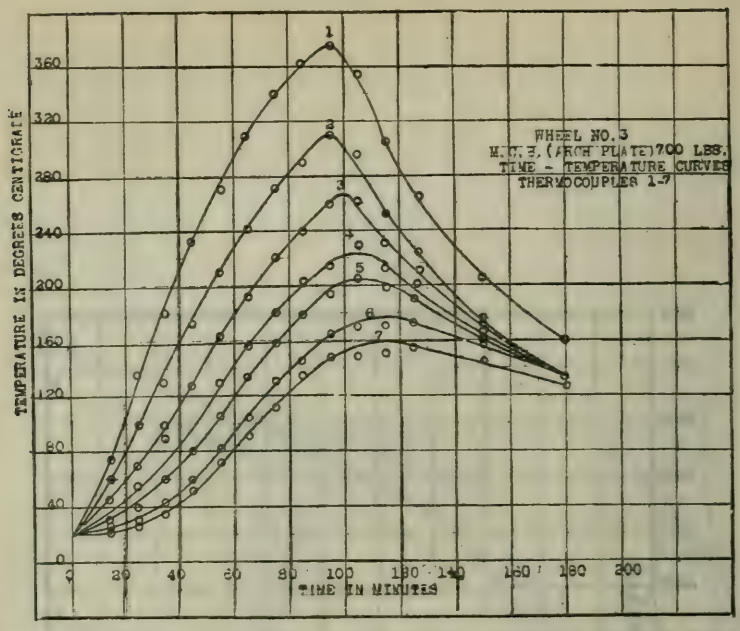


FIG. 24.—*Curves showing rise of temperature with time for various locations in wheel 3*

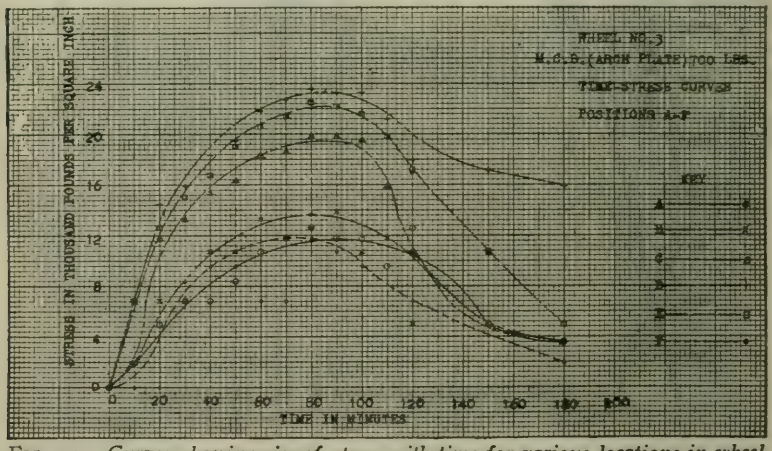


FIG. 25.—*Curves showing rise of stress with time for various locations in wheel 3*

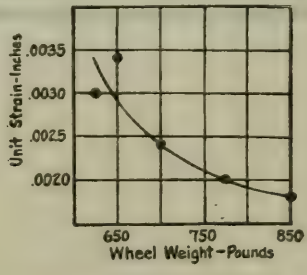


FIG. 26.—*Relation of strain to weight for arch-plate wheels of various weights*

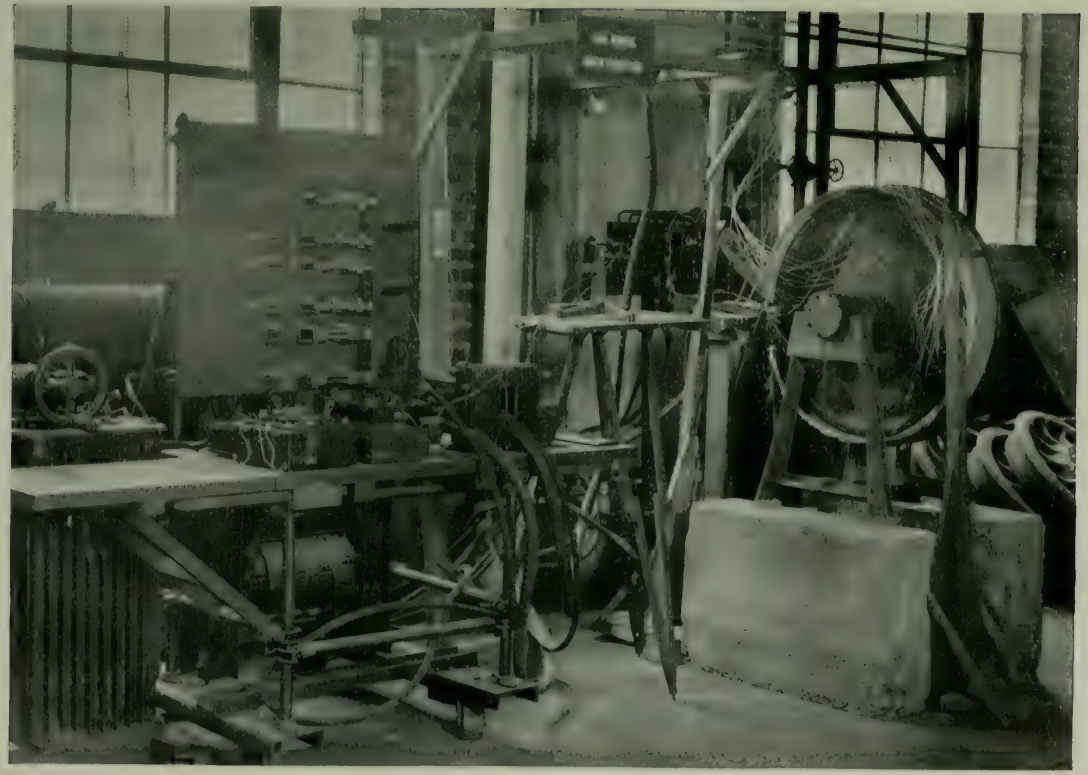


FIG. 15.—*Car wheel in test stand ready for special Bureau of Standards thermal test*

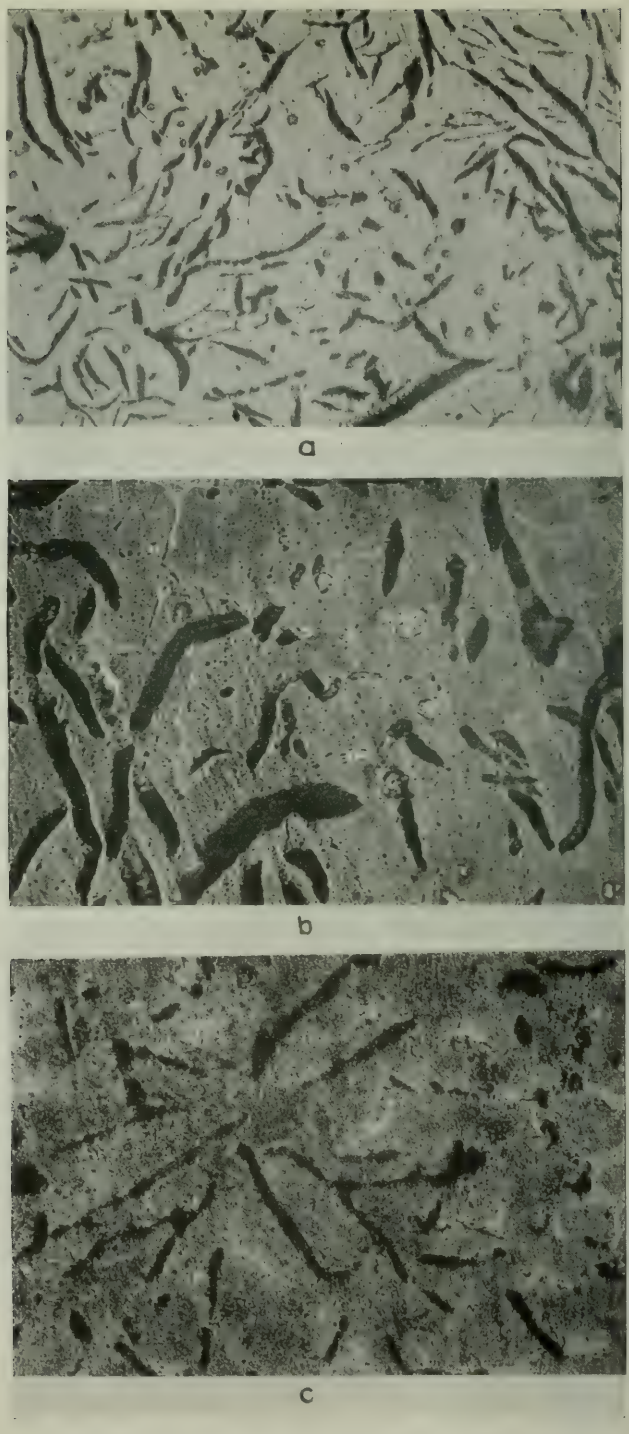
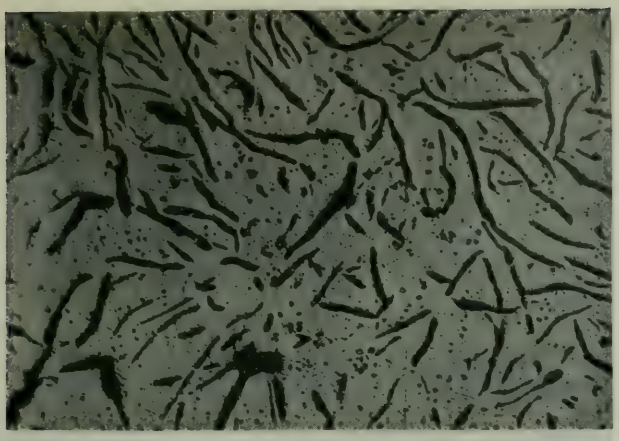


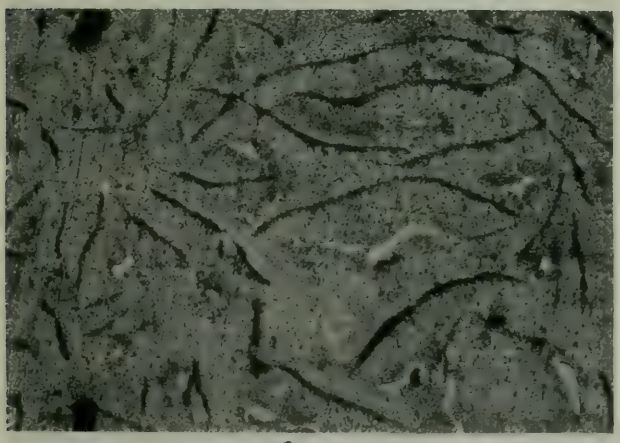
FIG. 18.—*Specimen from wheel 5, foundry "A"*

(*a*) Polished but unetched; × 50. Most of the small black specks represent inclusions principally of sulphide; the graphite flakes (wide black lines) are much larger than these
(*b*) Heat-tinted specimen; × 100. The light branching areas are the phosphide eutectic; the white spots are the sulphide
(*c*) Specimen etched in 5 per cent picric acid, × 100. The gray background is the pearlitic matrix of the iron; the light branching islands are the phosphide eutectic



a

b



c

FIG. 19.—*Specimen from wheel 9, foundry "B"*

(*a*) Polished but unetched; × 50. Most of the small black specks represent inclusions principally of sulphide; the graphite flakes (wide black lines) are much larger than these

(*b*) Heat-tinted specimen; × 100. The light branching areas are the phosphide eutectic; the white spots are the sulphide

(*c*) Specimen etched in 5 per cent picric acid, × 100. The gray background is the pearlitic matrix of the iron; the light branching islands are the phosphide eutectic

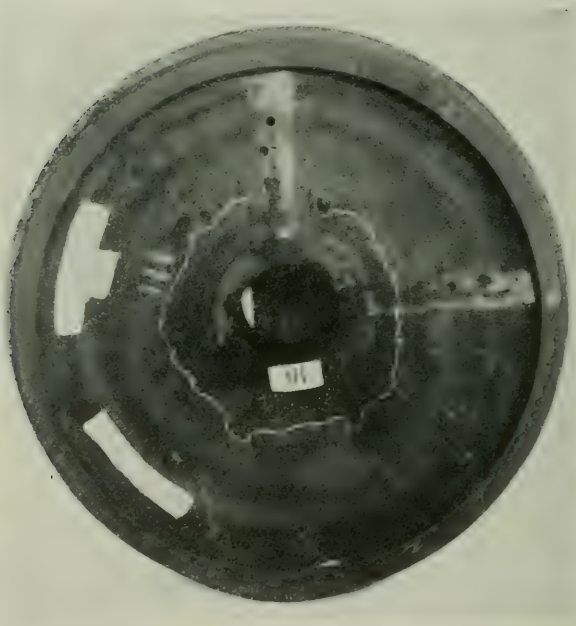


FIG. 23.—*Cracks in wheel 18 after special thermal test*

DEPARTMENT OF COMMERCE

926 4

TECHNOLOGIC PAPERS

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No. 210

THE REDWOOD VISCOMETER

BY

WINSLOW H. HERSCHEL, Associate Physicist
Bureau of Standards

APRIL 10, 1922

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THE REDWOOD VISCOMETER

By Winslow H. Herschel

ABSTRACT

The Redwood viscometer was selected for calibration because there appeared to be some doubt whether or not the instrumental constants varied with the temperature. By the use of oils whose viscosity had been determined in a capillary tube instrument the equation was obtained:

$$\text{kinematic viscosity} = 0.00260\,t - \frac{1.88}{t}$$

where t is the time of flow in seconds.

Two common errors in viscosimetry were investigated, with the following conclusions:

1. That the error due to inaccuracy in the Meissner formula for average head is negligible in ordinary work.

2. That the error due to cooling of the oil after leaving the outlet tube may be neglected at low temperatures but should be corrected at temperatures near the boiling point of water. Thus, any observed variation in instrumental constants at different temperatures is probably due to the last-mentioned error, so that viscosimeters may be calibrated at any convenient temperature, and outlet tubes may be made of any suitably durable and noncorrosive material without regard to its coefficient of expansion.

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1. INTRODUCTION

It is generally believed necessary to standardize viscosimeters or viscometers at more than one temperature. If this is correct, all instruments of a given type must be made of material of approximately the same thermal coefficient of expansion, and the use of only one calibrating liquid at two different temperatures would be inadequate, even if the experimental error were assumed negligible.

Waidner [1] found conversion factors between the Saybolt Universal, Engler, and Redwood instruments by flow tests made at 70 to 210° F (21.1 to 98.9° C) and concludes:

The fact that these factors (for the Saybolt Universal and Engler viscosimeters) show no systematic variation with temperature therefore indicates that if the oil in

[1] C. W. Waidner, Proc. A. S. T. M., 15, part 1, p. 286; 1915.

the jet is not at the same temperature as the oil in the main portion of the viscosimeter any effect due to this cause is the same for the two types of instruments. The conversion factors found for the Redwood viscosimeter seemed, on the other hand, to depend not only upon the efflux times but to some extent upon the temperature.

In previous work by the author [2] the range of temperatures was insufficient to throw any light on this subject, and it therefore seemed desirable to determine whether or not conversion factors depended solely upon the kinematic viscosity or upon kinematic viscosity and temperature.

2. DESCRIPTION OF REDWOOD VISCOMETER

The Redwood viscometer,[3] which is standard in England, is of the same general efflux type as the Engler, of Germany, and the Saybolt Universal, which has been adopted as standard for lubricating oils in the United States.[4] The Redwood differs from these other instruments in being provided with an agate outlet tube, a feature which Redwood, in designing his instrument in 1885, copied from an earlier instrument of Charles Rumble.[5]

The instrument consists of a silvered brass container about 1⅞ inches in diameter by about 3½ inches in depth (4.76 by 8.89 cm). A 1-inch (2.54 cm) tube, closed at the lower end, projecting at an angle of 45 degrees from the side of the bath near the bottom, provides a means of heating the bath without danger of overheating the agate. The bath is also furnished with a drain cock.

The flow of oil is controlled by a small brass sphere attached to a wire, the sphere resting in a hemispherical cavity in the agate. This is open to the same objection as the skewer used with the Engler instrument, that it might cause wear of the outlet tube. It is also apt to leak, so that the flask can not be placed under the instrument until immediately before starting the flow.

In the Redwood instrument, as in the Engler, the thermometer is left in the oil during the test. As the bulb is completely submerged at the end, there is no question in regard to accuracy of reading, as with the Engler, where the bulb is partly exposed. The thermometer stem must be of standard diameter, but the dimensions of the bulb have no influence upon the average head.

---

[2] B. S. Tech. Papers, Nos. 100, 112, and 125.

[3] For illustrations of this instrument see Holde-Mueller, Examination of hydrocarbon oils, p. 114, 1915; L. Archbutt and R. M. Deeley, Lubrication and lubricants, p. 167, 1912; B. Redwood, A treatise on petroleum, 2, p. 276, 1913.

[4] A. S. T. M., Standards adopted in 1920, p. 104; Bulletin No. 5, Committee on Standardization of Petroleum Specifications, p. 28, issued by the Bureau of Mines, 1921; Tests and testing standards adopted by the National Petroleum Association, Sept. 22, 1920.

[5] B. Redwood, Jour. Soc. Chem. Ind., 5, p. 124–5; 1886.

The height of filling is determined by a single gage point instead of the three points of the Engler and the overflow rim of the Saybolt. The instrument is provided with leveling screws.[6]

3. DIMENSIONS

The essential dimensions of the Redwood viscometer are given in Table 1, according to different experimenters.

TABLE 1.—Dimensions of Redwood Viscometer

Name of dimension	Higgins [a]		Meissner [b] No. 1263	Bureau of Standards	
	Normal	Tolerance		No. 1004	No. 1025
	cm	cm±	cm	cm	cm
Diameter of outlet tube d	0.15	0.003	0.158	[c] 0.1654	0.1583
Length of outlet tube, l	1.00	.01	1.023	.9853	.9639
Height of gage point above bottom of outlet tube, h_1	9.25	[d] .64	9.615	8.861	9.400
Diameter of container, D	4.68	.02	4.658	4.589	4.695
Average head (calculated) h	[e] 7.67		8.059	7.211	7.838
Diameter of stem of oil-cup thermometer	.63				
Diameter of bulb of oil-cup thermometer	.80				
External diameter of agate, upper end f	1.27	.10			
External diameter of agate, lower end f	1.15	.10			
Height of base of container g	.80	.05	.852		

[a] W. F. Higgins, Collected researches, National Physical Laboratory, **11**, p. 5; 1914.

[b] W. Meissner, Chem. revue über die fett und harz industrie, **19**, p. 9; 1912.

[c] This is considerably above the normal dimension reported by Higgins, but Archbutt and Deeley, p. 166, give d as "very nearly" 0.17 cm, with l=1.2 cm.

[d] Higgins gives the initial head in two parts, the height of gage point above the upper end of outlet tube being 8.25±0.63.

[e] Not given by Higgins.

[f] The importance of these dimensions appears to be mainly in shop construction.

[g] This is the height of junction of cylindrical portion of oil cup with concave bottom of cup above upper end of outlet tube.

The last dimension of Table 1 appears to be needlessly restricted. As 50 cc of oil are run out in a test, the oil level falls 2.96 cm, so that this dimension could have a maximum value of 5.29 cm (instead of 0.85), and the oil surface at the end of run would still be within the cylindrical part of the container, which is a necessary condition in order that the average head may be correct.

The bulb of the thermometer must be placed somewhere within the above-mentioned 2.96 cm, so as not to be exposed at the end of run and so as not to be too near the outlet tube and thus obstruct the flow. It seems probable that more reproducible results could be obtained if the exact location were specified.

There is some uncertainty about the standard dimensions, because Higgins says he expressed them in millimeters for conven-

[6] For a consideration of the error due to inaccuracy in leveling see W. F. Higgins, Collected researches, National Physical Laboratory, **11**, p. 6; 1914.

ience in comparing the Redwood and Engler instruments. This might be taken to imply that the real standardization is in inches. The diameter of the thermometer stem, for example, is obviously the equivalent of 0.25 inch, but the equivalent in inches of the inside diameter of the outlet tube is not so obvious, and it may be standardized in the metric system or have no other standardization than that of flow tests.

As has been noted in previous papers the Meissner formula for average head is not exact, because the kinetic energy correction was neglected in its derivation. The author is indebted to Dr. H. L. Dryden of this Bureau for an accurate equation for determining the average head when the kinetic energy correction is not neglected.[7]

For most purposes it is accurate enough to use Meissner's formula

$$h = \frac{h_1 - h_2}{\log e\left(\frac{h_1}{h_2}\right)} \qquad (2)$$

as has been done throughout this paper. If the accuracy of the experimental work or the large value of $h_1 - h_2$ justifies it, equation (2) may be used to get a preliminary value of the kinematic viscosity and to calculate C (see footnote 7), using the approximate values of $L = l + 0.25\ d$ and $m =$ unity, or more accurate values if known.

For the Saybolt Universal viscosimeter of normal dimensions the average head is 7.36 cm by equation (2) and 7.54 by equation (1), with t having a minimum value of 32 seconds. The maximum possible error due to using Meissner's formula is thus 2.4 per cent. With the Redwood instrument, assuming a kinematic viscosity of 0.025, the average head is 5.67 cm by equation (1) and 5.63 by equation (2), the difference of 0.7 per cent being negligible in the present work, since, as it should be remembered, this is the maximum error and decreases as the viscosity increases.

---

[7] Dryden's equation is as follows:

$$1 - \sqrt{1 + Ch} = \frac{\frac{1}{2}(y_2^2 - y_1^2) + y_1 - y_2}{y_2 - y_1 + \log e\left(\frac{y_1}{y_2}\right)} \qquad (1)$$

where $y_1 = 1 - \sqrt{1 + Ch_1}$

$y_2 = 1 - \sqrt{1 + Ch_2}$ (where h_2 = Final head at end of run),

m = coefficient of kinetic energy correction,

$C = \frac{g\, d^4\, m}{256\, (k.v.)^2\, L^2}$ $k.v.$ = kinematic viscosity, $= \frac{\text{absolutely viscosity in poises}}{\text{density in grams per cc}}$,

L = effective length of outlet tube = measured length + Couette correction,

g = acceleration of gravity = 981 cm per sec.^{2}

4. THE COOLING ERROR

It has long been known that there is an error with most commercial viscosimeters due to the cooling of the oil after it leaves the outlet tube, the effect being the same as if the flask were too large. To obviate this difficulty with the Engler viscosimeter, Engler and Kunkler [8] designed an instrument in which the flask is inclosed in a double-walled air bath. With the Barbey ixometer, with which the recorded "fluidity" is the volume discharged in cubic centimeters per hour, when the test is run for 10 minutes under a constant head, the volume is not read until the flask has been reheated to the nominal temperature of test.

In the directions for the Redwood viscometer Archbutt and Deeley say:

> If the test is to be made at a temperature more than a few degrees above or below that of the air of the room, the flask must be immersed in a bath of liquid heated to the testing temperature, or the body of the flask may be surrounded by a thick layer of cotton wool contained in a beaker, the neck and graduation mark being left exposed to view.

It is obvious that any conversion table would be inaccurate if used for comparison between readings of a Redwood viscometer when the above direction was obeyed and a Saybolt Universal instrument for which no such direction has been given. It will be assumed that the true conversion table which is desired is accurate when both instruments have been corrected for the cooling error, either by keeping the flask warm or by applying a correction to the observed time when necessary.

Fig. 1, which was calculated from Table 2, may be used to estimate the cooling error. Table 2 is in accord with former publications of the Bureau of Standards,[9] but gives the information in more convenient form for use in viscosimetry.

The density at 60° F (15.6° C) in grams per cubic centimeter may be taken as 0.001 less than the specific gravity as given in Table 2.

Fig. 2 is also needed to find the cooling error and has been calculated for the Saybolt Universal and Engler viscosimeters as well as the Redwood. If there is any appreciable error in the flask itself, the net or combined error must be used in entering Fig. 2 in order to get the combined error due to incorrect volume of flask and to cooling. The lines marked "max." and "min." show errors in time of flow due to the departure of the dimensions from

[8] L. Archbutt and R. M. Deeley, Lubrication and lubricants, pp. 168, 175, 1912; B. Redwood, A treatise on petroleum, 2, p. 280, 1913.

[9] H. W. Bearce and E. L. Peffer, B. S. Tech. Papers, No. 77, 1916; B. S. Circular No. 57, 1916.

the normal or mean values while still being "standard" or within the permissible variations. The dotted line for the Redwood viscometer was calculated from experimental data of Higgins, while the other lines are based solely upon calculated variations in average head due to variations in volume discharged.

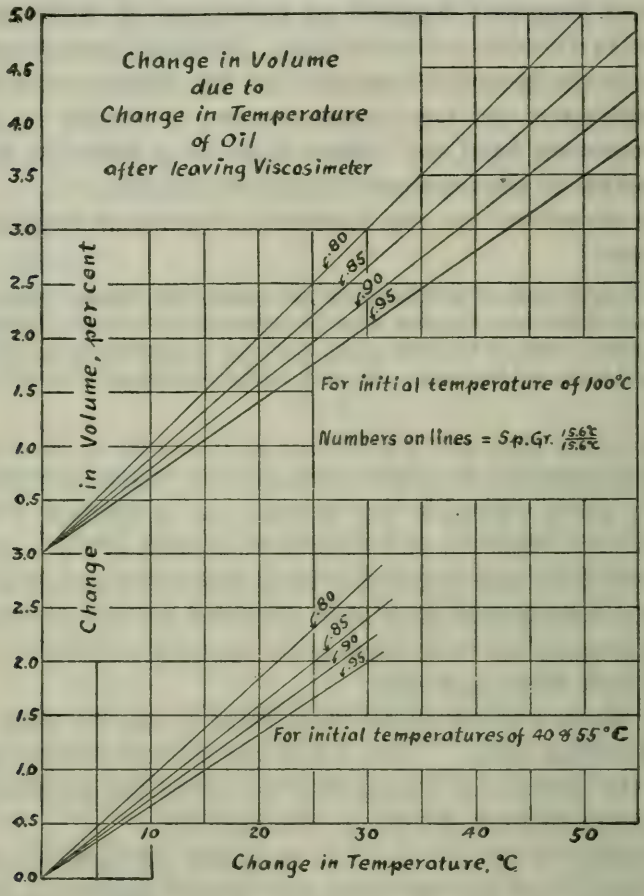

FIG. 1.—*Diagram showing change in volume of oil after leaving outlet tube*

Considering only instruments of normal dimensions, it will be seen that the error in time of flow is slightly greater than the error in volume for the Redwood and Engler instruments and about twice as great as the error in volume with the Saybolt Universal. The cooling error can not be considered negligible when tests are made at 210° F (98.9° C), and it seems probable that differences in conversion factors at different temperatures which might be observed could be ascribed to differences in cooling error, rather

than to a difference in the thermal coefficient of expansion of the outlet tubes.

TABLE 2.—Change in Density of Petroleum Oils with Change in Temperature

Specific gravity $\frac{15.6°}{15.6°}$ C	Change in density per degree—		Specific gravity $\frac{15.6°}{15.6°}$ C	Change in density per degree—	
	C	F		C	F
0.630	0.00098	0.000544	0.798	0.00073	0.000406
.640	.00096	.000534	.808	.00072	.000400
.650	.00094	.000522	.817	.00071	.000395
.659	.00093	.000517	.827	.00070	.000389
.669	.00092	.000511	.837	.00069	.000383
.679	.00090	.000500	.847	.00068	.000378
.689	.00089	.000495	.857	.00068	.000378
.699	.00088	.000489	.867	.00067	.000372
.709	.00087	.000484	.877	.00067	.000372
.719	.00085	.000472	.887	.00067	.000372
.729	.00084	.000467	.897	.00066	.000367
.739	.00083	.000461	.907	.00066	.000367
.748	.00081	.000450	.917	.00066	.000367
.758	.00080	.000445	.927	.00066	.000367
.768	.00078	.000433	.937	.00066	.000367
.778	.00076	.000422	.947	.00066	.000367
.788	.00075	.000417	.957	.00066	.000367

The difference in temperature between the nominal temperature of test and the temperature of flask at end of run would naturally depend upon the room temperature, the viscosity of the oil, and the temperature of test. Fig. 3 shows that the cooling of the flask, and hence the cooling error, is negligible at low temperatures. The data are insufficient to indicate the extent to which the amount of cooling will vary with the room temperature or with the temperature of the oil bath for a given nominal temperature of test.

The American Society for Testing Materials [10] puts the responsibility for selecting the proper bath temperature upon the operator and merely says:

> The bath shall be held constant within 0.25° F (0.14° C) at such a temperature as will maintain the desired temperature in the standard oil tube.

It is commonly supposed that for the Saybolt Universal viscosimeter the bath should be kept at 100.25, 130.5, and 212.0° F (37.9, 54.7, and 100° C), respectively, for the three standard temperatures, but tests at the Bureau of Standards seem to indicate that

[10] Standards adopted in 1920, p. 105.

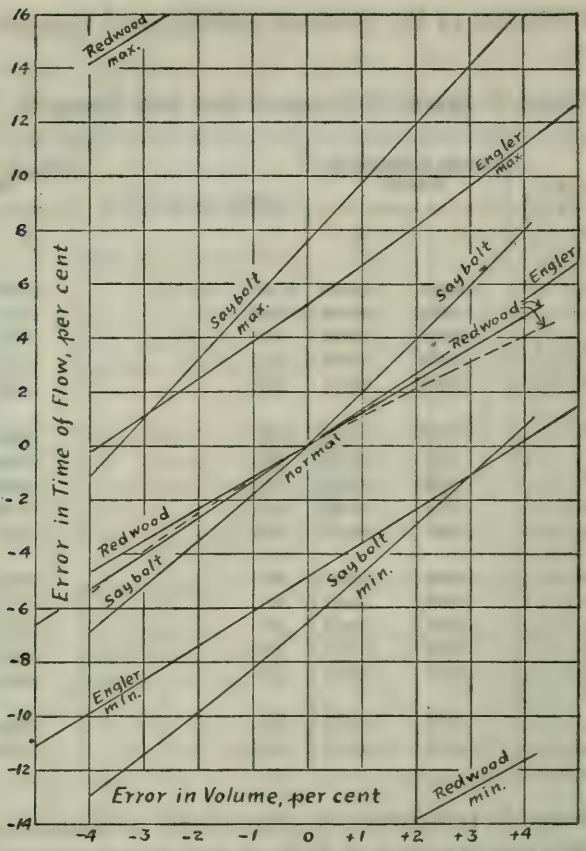

FIG. 2.—*Diagram for determining cooling error*

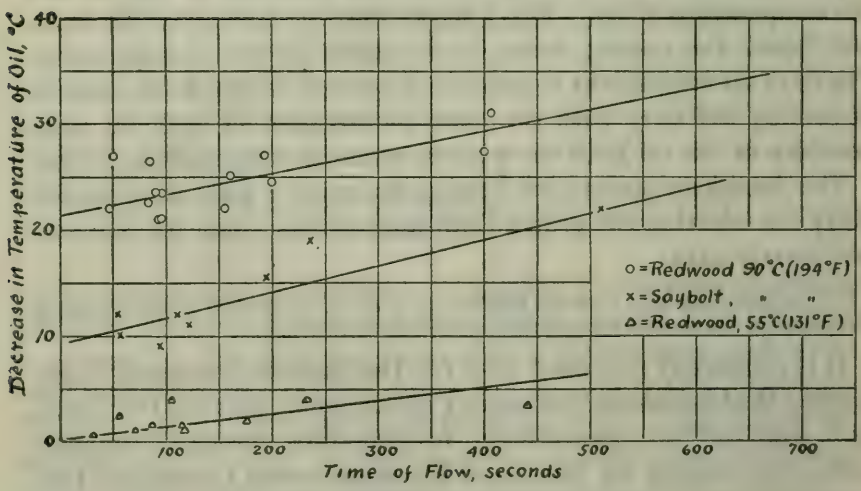

FIG. 3.—*Diagram showing decrease in temperature of oil in flask*

these temperatures are too low. The work was planned at a time when a committee of the American Society for Testing Materials [11] had proposed as standard temperatures, 20, 40, 55, and 100° C (68, 104, 131, and 212° F), and the proper excess of bath temperature over the nominal temperature of test was found to be as shown in Table 3.

TABLE 3.—Excess of Bath Over Test Temperature

Saybolt viscosity in seconds	Temperature of test—					
	104° F=40° C		131° F=55° C		212° F=100° C	
	° C	° F	° C	° F	° C	° F
32	0.7	1.3	0.8	1.4	1.3	2.3
60	.7	1.3	.8	1.4	1.3	2.3
90	.9	1.6	.9	1.6	1.4	2.5
120	.9	1.6	.9	1.6	1.4	2.5
150	1.0	1.8	1.0	1.8	1.6	2.9
180	1.0	1.8	1.1	2.0	1.8	3.2

If a steam bath at 212° F does not keep the oil under test at a temperature of 210° F, this standard temperature has no value whatsoever, and it is objectionable in any case, because there is always danger that the variations of steam temperature with the barometer will be overlooked.

The subject of bath temperature is more important with the Saybolt than with the Redwood or Engler instruments, because with the two latter the thermometer is kept in the oil during the run. A viscosimeter of the Saybolt type which is provided with a cover to support the thermometer in the oil during the test, is in use at the Bureau of Standards and gives the same time of flow as the usual Saybolt instruments. The instrument is provided with interchangeable tips of monel metal of the standard dimensions for the Saybolt Universal and Saybolt Furol viscosimeters.

5. STANDARDIZATION

In cases where a calibrating liquid of greater viscosity than water is required it is common to make use of sucrose or glycerin solutions, although they are both objectionable at high concentrations. With the former the viscosity changes very rapidly with the concentration, while the density which is used to determine

[11] Proc. A. S. T. M., 17, part 1, p. 463, 1917; 18, part 1, p. 321, 1918.

the concentration changes very slightly. Glycerin is objectionable because it is hygroscopic and because, according to Bawtree [12]—

> Glycerin is not to be depended upon as a standard of viscosity. It possesses some internal structure which is broken down by repeatedly passing the same sample through the instrument till a minimum viscosity is reached. Physicists who have relied upon glycerin for standardizing their various viscometers have questioned this result, but glycerin manufacturers state that this state of stress in the material is an ordinary factor with which they have to deal and that the Hadfield-Bawtree viscometer results bear out their own experience.

Rape seed or colza oil is commonly used in Europe as a lubricant, and it is used to some extent in this country for compounding. Its viscosity approaches the average of that for petroleum lubricating oils. It is therefore used as a calibrating liquid for the Barbey ixometer and the Martens[13] oil-friction testing machine, as well as for the Redwood viscometer.

Redwood was aware that a calibration by means of flow tests with a single liquid at a single temperature was inadequate and must be supplimented by standard dimensions. Speaking of glass pipettes, he says:

> It is a serious objection to the pipette that the results afforded vary to some extent with the shape of the constricted portion of the tube. Two pipettes may be constructed with jets of such size that they deliver equal quantities of a given oil at a given temperature in a given time; but if the jets vary materially in form the two instruments will not furnish concordant results with oils of greater or less viscosity than that of the oil with which they were standardized.

This applies, though to a less extent, to all efflux viscosimeters, even when of standard dimensions, because it is always necessary from practical considerations to allow a certain variation or tolerance on all dimensions. Redwood makes his final adjustments by varying the hydrostatic head, and says:

> The necessary amount of correction is so small that I have not, in practice, found that any objection attaches to the method adopted.

It will be noted that, according to the equation for viscous flow, if two instruments are to agree at all viscosities it is necessary only that the lengths of outlet tube shall be equal, and that there shall be equal values of d^4h. The first requirement is met by the standard dimensions and the second by adjusting the head. According to Higgins—

> The diameter of the jet in the Redwood viscometer is not rigidly fixed by measurement, but it is to be of such a size that 50 cc of rape oil will have a time of flow at 60° F. (15.6° C.), equal to 535 seconds, when the filling mark is adjusted to within 6.3 mm of its normal position. This corresponds approximately to a permissible variation of ± 2 per cent in the diameter of the jet.

---

[12] A. E. Bawtree, Jour. Oil and Color Chemists Assn., 3, p. 109, 1920.

[13] Holde-Mueller, Examination of hydrocarbon oils, p. 124, 1915.

In reality the values of 535 seconds for the time of flow and 0.915 as assumed for the density are purely arbitrary, as shown by Table 4 from tests of 10 samples by Crossley and Le Sueur.[14]

TABLE 4.—Density and Viscosity of Rape-Seed Oil, According to Crossley and Le Sueur

Specific gravity at 60° F=15.6° C	Time of flow in seconds, Redwood viscometer, at 70° F=21.1° C
0.9141 (minimum)	413.8
.9165	369.4 (minimum)
.9171	464.6 (maximum)
.9177 (maximum)	371.0

The variation in viscosity is therefore about 20 per cent, as compared with 2.5 per cent for castor oil.[15] Archbutt [16] found a variation of 27 per cent for 22 samples of rape-seed oil. In short, there seems to be no value to rape-seed oil as a calibrating liquid except the psychological value of a tradition, and a mineral oil would serve the purpose much better because changing less in viscosity with time.

It is a question whether in the manufacture of the Saybolt Universal viscosimeter a certain barrel of oil or a certain instrument is taken as the ultimate standard, to which the standard dimensions secure merely an approximation. With the instruments as hitherto constructed, it has been found that a burr forms at the upper end of the outlet tube and causes an increase in the time of flow. This burr is apparently caused by the rubbing of the thermometer bulb across the upper end of the outlet tube.

Redwood says concerning his instrument:

> The author attaches considerable importance to the employment of agate in the construction of the jet, as this material is not liable to become worn or injured, even if the instrument is subjected to somewhat rough usage. He has had one of these viscometers in almost daily use in his laboratory at temperatures ranging from 70 to 250° F (21.1 to 121.1° C) for the past 25 years, and the jet shows no sign of wear.

If this means there is no change in the time of flow for a definite chemical compound, it is a remarkable record. Neither oil nor instrument is satisfactory as an ultimate standard, since the viscosity of a sample may change with time, and any instrument is liable to injury or destruction by fire or otherwise. If a certain sample of oil is the standard, then it is necessary periodically when the sample becomes exhausted to select a new sample, with danger

[14] Quoted by J. Lewkowitsch, Chemical technology and analyses of oils, fats, and waxes, 2, p. 199, 1909.
[15] Winslow H. Herschel, B. S. Tech. Papers, No. 112, p. 24, 1919.
[16] L. Archbutt, Jour. Soc. Chem. Ind., 5, pp. 132, 310, 1886.

of a gradual accumulation of errors. The only satisfactory ultimate standard must be based on numerical values, as, for example, an equation of the form

$$\text{kinematic viscosity} = k.\ v. = At - \frac{B}{t}, \qquad (3)$$

as tentatively adopted by the National Petroleum Association [17] for the Saybolt Universal, Engler, and Redwood instruments.

6. RESULTS OF TESTS

As the Bingham viscometer, which was used in determining the viscosities of calibrating liquids, can not conveniently be run at

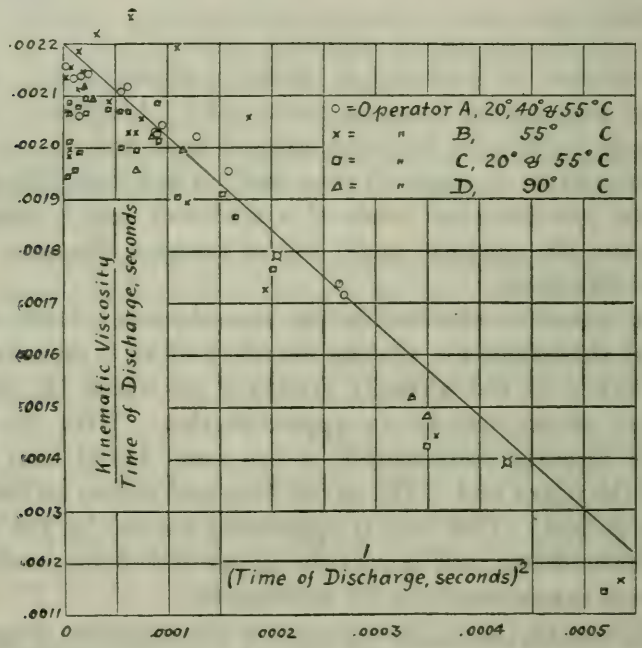

FIG. 4.—*Higgins diagram for Saybolt Universal viscosimeter No. 109*

100° C (212° F) the somewhat lower temperature of 90° C (194° F) was selected in addition to the temperatures of 20, 40 and 55° C previously mentioned in connection with Table 3. The methods of determining instrumental constants from the results of flow tests have been fully described in previous papers.

Figs. 4 and 5 show Higgins and Herschel diagrams for Saybolt Universal viscosimeter No. 109. In Fig. 4 the graph is drawn from equation (3), with $A = 0.00220$ and $B = 1.80$ as determined in previous work. It seems possible that the points indicate a

[17] Tests and testing standards recommended by the department of standards and tests, N. P. A., Sept. 22, 1920. See also Proc. A. S. T. M., **21**, p. 362; 1921.

lowering of the graph or a decrease in the constant A, due to the burr previously referred to. This was to be expected, since it was found after these tests were finished that a perceptible burr had formed at the top of the outlet tube, which had to be removed to restore the instrument to standard dimensions. No systematic variation of A with the temperature can be observed.

In Fig. 5 the calibration graph was drawn as calculated from the dimensions of instrument No. 109 and with the Couette and kinetic energy corrections also taken from Bureau of Standards Technologic Paper No. 112. The decrease in the value of A is here indicated by the location of most of the points to the right of the graph. Tests of operator B are apparently less exact, and tests at very high viscosities—say, with values of Reynold's criterion below 10—should be disregarded on account of error in the assumed viscosities of the calibrating liquids.[18]

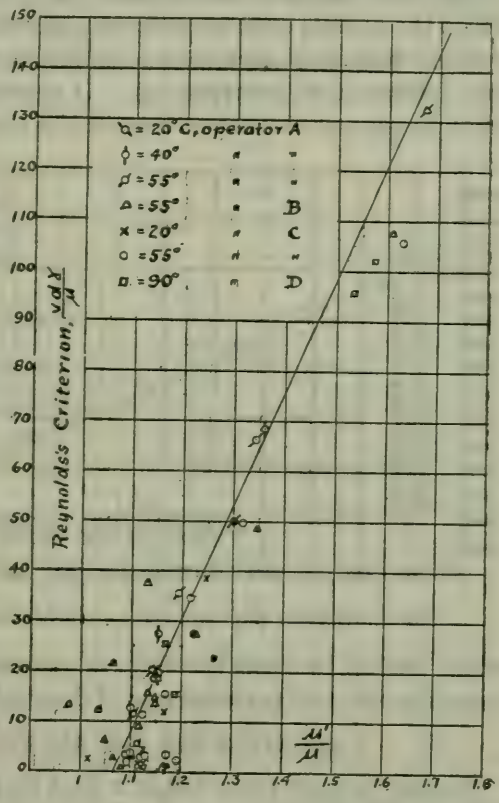

FIG. 5.—*Herschel diagram for Saybolt Universal viscosimeter No. 109*

Fig. 6 shows a Higgins diagram for the Redwood instrument. The change in slope near the bottom of the graph indicates the critical velocity, which is the highest velocity for which the instrument should be used. The time of flow is here 30.4 seconds, while Reynold's criterion is 700, as compared with 800 for the Saybolt Universal viscosimeter at the critical velocity. The dotted line, which represents fairly well the results of Archbutt and Deeley, was calculated from a diagram giving results of tests by the Texas Co. on instrument No. 1326.[19]

[18] The source of error will be discussed in another paper. It will be sufficient to point out here that the error is indicated at high viscosities by the points being too low on a Higgins diagram (Fig. 4) or too far to the right on a Herschel diagram (Fig. 5).

[19] Lubrication, 7, p. 5, May, 1921.

Figs. 7 and 8 show Herschel diagrams for Redwood viscometers Nos. 1004 and 1205. As in Fig. 5 there is no indication of any effect of a change in temperature. The points obtained at 90° C (194° F) were corrected for cooling error, the maximum correction in time of flow being 2.8 per cent, or slightly less than the maximum of 3.4 per cent for the Saybolt Universal, Figs. 4 and 5. The error was negligible at lower temperatures.

It is believed that this proves that within the experimental error there is no change in calibration due to change in temperature provided the cooling error is corrected, and that the commonly accepted opinion that it is necessary to calibrate viscosimeters at more than one temperature is erroneous. It shows, also, that the coefficient of expansion of the outlet tube is not important, and that the material should be chosen solely on grounds of ease and accuracy of manufacture and permanency of dimensions when once completed.

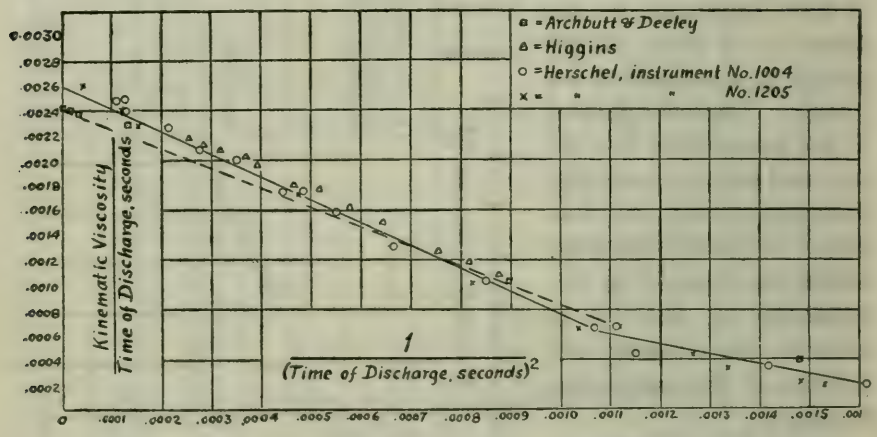

FIG 6.—*Higgins diagram showing critical velocity for Redwood viscometer*

7. EQUATION FOR THE REDWOOD VISCOMETER

It may be seen from Table 1 that instrument No. 1025 is not of standard dimensions, the outlet tube being too short. Fig. 8 indicates that the Couette correction has a negative value, which is unusual, and the author has previously expressed the opinion that it is always positive.[20] Knibbs,[21] who takes the correction as $\frac{nd}{2}$, found that n was sometimes positive and sometimes negative, and says:

> No general value, unless it be zero, can be assigned to n. Hence, no correction should be applied to the length of a tube unless experiments therewith clearly indicate its propriety.

[20] Trans. A. S. C. E., **84**, p. 527; 1921.
[21] G. H. Knibbs, Jour. and Proc. R. S., New South Wales, **29**, p. 105, 1895.

For these reasons the tests on instrument No. 1025 have been disregarded and the Redwood equation based entirely on tests with instrument No 1004.

From Fig. 7 and the dimensions of Table 1 the Couette correction $= 0.01$ cm $= 0.06\,d$. That this is much less than found for the Saybolt Universal viscosimeter may be due to the fact that the piece of agate in the Redwood instrument is concave at the top and convex at the bottom, which probably reduces the effect of

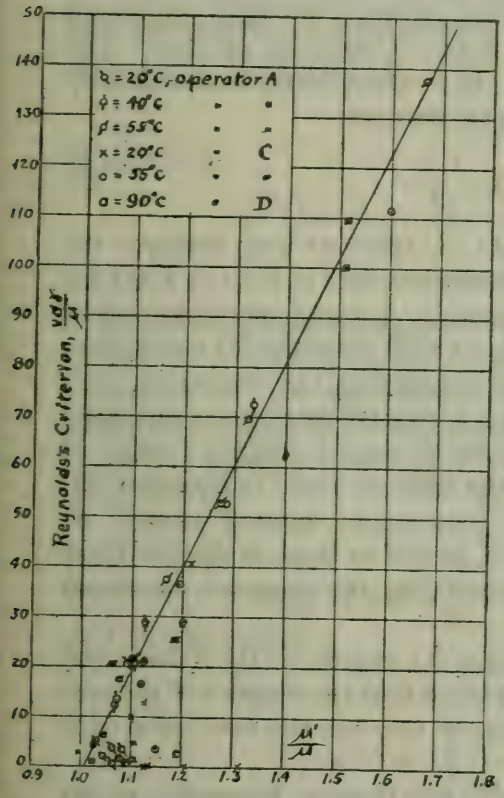

FIG. 7.—*Herschel diagram for Redwood viscometer No. 1004*

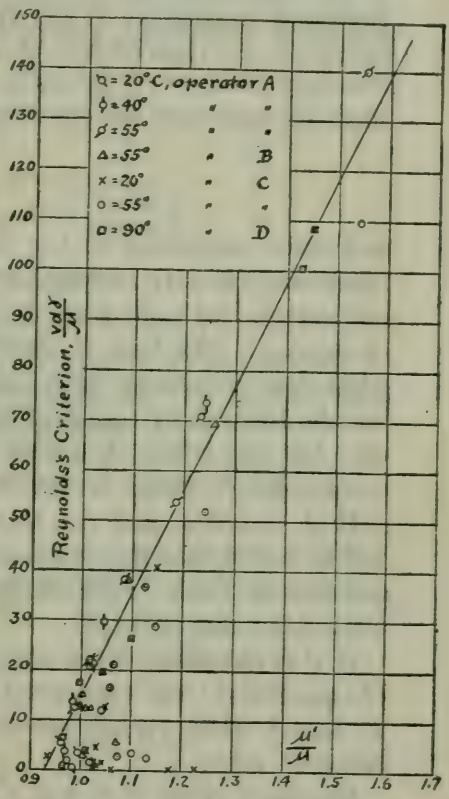

FIG. 8.—*Herschel diagram for Redwood viscometer No. 1025*

surface tension. Fig. 7 also gives the value of 0.953 for the coefficient m of the kinetic energy correction.

In equation (3)

$$A = \frac{\pi\, g\, d^4\, h}{128\, Q\, L}, \qquad (4)$$

where Q is the volume of oil run out in the measured time, or 50 cc, for the Redwood instrument. The second instrumental constant may be found by the equation

$$B = \frac{Q\, m}{8\, \pi\, L}. \qquad (5)$$

From equations (3) to (5), the dimensions of the instrument, and the above values of m and the Couette correction, the equation for Redwood instrument No. 1004 may be obtained as

$$k.\ v. = 0.00259\ t - \frac{1.905}{t}. \qquad (6)$$

There is considerable difficulty in correcting equation (6) so that it will apply to an instrument of normal dimensions, since the Redwood viscometer is partly standardized by dimensions and partly by the time of flow of a liquid of unknown vicosity. The attempt will however be made. Since the velocity of flow is very small for rape-seed oil, equation (3) becomes

$$t = 535 = \frac{k.\ v.}{A}, \qquad (7)$$

and since, according to the data of Archbutt and Deeley,[22] the kinematic viscosity of rape-seed oil at 60° F (15.6° C) is 1.223 for one sample and 1.285 poise for another, A would approach 0.00229 or 0.00241. The lack of agreement with equation (6) emphasizes what has previously been said concerning the vagueness of a standardization by means of such a variable material as rape-seed oil. On the whole, it seems best to accept Higgins's value of 0.00260 for A, which is almost the same as found in equation (6).

If $A = 0.00260$ and $L = 1.01$, equation (4) gives $d = 0.163$. It will be noted that this value of d, as well as those in the last three columns of Table 1, are all greater than the supposed maximum allowable value of 0.153.

If B is calculated from equation (5) exactly as the value 1.905 of equation (6) was calculated, except that the length l of the outlet tube is given its normal value of 1.00 cm, the new value of B becomes 1.877.

Higgins's value of B was 1.715, but it seems impossible to get this value on any assumption in accordance with the tests. If the Couette correction were negative, as indicated by tests on instrument No. 1205, then A as well as B would be increased, and both constants would be in poorer agreement with other experimenters. There is no evidence that the value of m should be decreased, as it is already less than the theoretical value of 1.12 or the value 0.989 previously found for the Saybolt Universal viscosimeter. If it is assumed that Higgins's instrument had the maximum allowable length of outlet tube, 1.01 cm and $L = 1.02$, it

[22] L. Archbutt and R. M. Deeley, Lubrication and lubricants, p. 190, 1912.

would follow from equation (5) that $B = 1.859$. To still further reduce the value of B it might be assumed that the Couette correction $= 0.466\ d$, as with the Saybolt, and that $d = 0.15 + 2$ per cent $= 0.153$ cm. This would give a value of $L = 1.08$ cm and $B = 1.755$, which is still higher than Higgins's value.

On the whole, the evidence appears to be that Higgins's values of $d = 0.15$ cm and $B = 1.715$ are both too low for an instrument of normal dimensions. The most probable value of B is 1.88, so that the complete equation for a Redwood viscometer of normal dimensions would be

$$k.\,v. = 0.00260\,t - \frac{1.88}{t}, \tag{8}$$

from which

$$t = 192.3\ k.\,v.\left(1 + \sqrt{1 + \frac{0.01952}{(k.\,v.)^2}}\right). \tag{9}$$

8. CONVERSION TABLES

In previous work[23] Higgins's equation was used tentatively as probably the best available, but this may now be replaced by equations (8) and (9). Similar equations for the Saybolt Universal and Engler instruments are as follows:

For the Saybolt Universal—

$$k.\,v. = 0.00220\,t - \frac{1.80}{t} \tag{10}$$

$$t = 227.3\ k.\,v.\left(1 + \sqrt{1 + \frac{0.01584}{(k.\,v.)^2}}\right), \tag{11}$$

and for the Engler—

$$k.\,v. = 0.00147\,t - \frac{3.74}{t} \tag{12}$$

$$t = 340.3\ k.\,v.\left(1 + \sqrt{1 + \frac{0.02196}{(k.\,v.)^2}}\right). \tag{13}$$

Equations (12) and (13) were derived for instrument No. 2204U with a water rate of 51.3 seconds, but they are the best available for an Engler instrument of normal dimensions.

Equations (8) to (13) have been used to calculate Tables 5 to 8, giving multiplying factors to convert readings of one instrument into those of either of the other two or into kinematic viscosity, which serves as an international language. Each table begins with the lowest viscosity for which the instrument mentioned in the first column should be used. The multiplying factors given in the last line hold good for all higher viscosities.

[23] Winslow H. Herschel, B. S. Tech. Papers, No. 112, p. 22, 1919.

9. CONCLUSION

1. There is no change in instrumental constants due to change of temperature of test, so that instruments may be calibrated at any convenient temperature, varying the viscosity either by change of temperature or by blending.

2. The error due to inaccuracy of the Meissner formula for average head is not serious.

3. The error due to change in volume of the oil after it leaves the outlet tube is not a major error in viscosimetry and is negligible at all usual temperatures of test except 210 or 212° F (98.9 or 100° C).

4. The most probable equation for the Redwood No. 1 or standard Redwood viscometer is

$$\text{kinematic viscosity} = 0.00260\, t - \frac{1.88}{t},$$

necessitating a slight change in the tentative tables given in Bureau of Standards Technologic Paper No. 112.

TABLE 5.—Viscosimeter Comparisons—Factors to Reduce Redwood Time to Saybolt Universal Time or Engler Degrees

Redwood time in seconds	Kinematic viscosity	Saybolt time / Redwood time	Engler degrees / Redwood time	Redwood time in seconds	Kinematic viscosity	Saybolt time / Redwood time	Engler degrees / Redwood time
30	0.0154	1.08	0.0365	80	0.1845	1.16	0.0349
32	.0245	1.09	.0363	85	.1989	1.16	.0349
34	.0332	1.09	.0361	90	.2131	1.17	.0348
36	.0414	1.10	.0360	95	.2272	1.17	.0348
38	.0493	1.10	.0359				
				100	.2412	1.17	.0348
40	.0570	1.11	.0358	110	.2689	1.17	.0347
42	.0645	1.11	.0357	120	.2964	1.17	.0347
44	.0717	1.12	.0357	130	.3236	1.17	.0347
46	.0788	1.12	.0356	140	.3506	1.18	.0347
48	.0854	1.13	.0355				
				150	.3775	1.18	.0347
50	.0924	1.13	.0354	160	.4043	1.18	.0346
55	.1088	1.14	.0354	180	.4576	1.18	.0346
60	.1247	1.14	.0353	200	.5106	1.18	.0346
65	.1401	1.15	.0352	225	.5766	1.18	.0346
70	.1552	1.15	.0351	250	.6425	1.18	.0345
75	.1700	1.16	.0350				

TABLE 6.—Viscosimeter Comparisons—Factors to Reduce Saybolt Universal Time to Engler Degrees or Redwood Time

[For additional values for the first two columns see W. H. Herschel and E. W. Dean, Bureau of Mines, Reports of Investigations, Serial No. 2201, January, 1921.]

Saybolt time in seconds	Kinematic viscosity	Engler degrees / Saybolt time	Redwood time / Saybolt time	Saybolt time in seconds	Kinematic viscosity	Engler degrees / Saybolt time	Redwood time / Saybolt time
32	0.0142	0.0337	0.928	85	0.1658	0.0305	0.862
34	.0219	.0334	.920	90	.1780	.0304	.860
36	.0292	.0332	.914	95	.1901	.0303	.858
38	.0362	.0330	.909	100	.2020	.0302	.856
40	.0430	.0328	.905	110	.2256	.0301	.855
42	.0495	.0326	.901	120	.2490	.0300	.854
44	.0559	.0324	.897	130	.2722	.0299	.853
46	.0621	.0322	.893	140	.2951	.0299	.852
48	.0681	.0319	.889	160	.3408	.0298	.851
50	.0740	.0317	.885	180	.3860	.0297	.850
55	.0883	.0315	.881	200	.4310	.0296	.849
60	.1020	.0313	.871	225	.4870	.0295	.848
65	.1153	.0312	.873	250	.5428	.0294	.847
70	.1283	.0310	.870	300	.6540	.0293	.847
75	.1410	.0308	.867	350	.7648	.0293	.846
80	.1535	.0307	.865	400	.8755	.0292	.846

TABLE 7.—Viscosimeter Comparisons—Factors to Reduce Engler Degrees to Saybolt Universal or Redwood Time

Engler degrees	Kinematic viscosity	Saybolt time / Engler degrees	Redwood time / Engler degrees	Engler degrees	Kinematic viscosity	Saybolt time / Engler degrees	Redwood time / Engler degrees
1.10	0.0166	29.7	27.5	2.30	0.1416	32.8	28.5
1.15	.0234	29.9	27.6	2.40	.1506	32.9	28.5
1.20	.0299	30.1	27.6	2.50	.1593	33.0	28.5
1.25	.0358	30.3	27.7	2.60	.1677	33.1	28.6
1.30	.0420	30.5	27.8	2.70	.1764	33.2	28.6
1.35	.0476	30.7	27.8	2.80	.1849	33.3	28.6
1.40	.0534	30.9	27.9	2.90	.1935	33.4	28.6
1.45	.0590	31.1	27.9	3.00	.2019	33.5	28.7
1.50	.0646	31.3	28.0	3.50	.2432	33.6	28.7
1.60	.0750	31.5	28.1	4.00	.2833	33.7	28.8
1.70	.0853	31.7	28.1	4.50	.3228	33.9	28.8
1.80	.0953	31.9	28.2	5.00	.3624	33.9	28.8
1.90	.1046	32.1	28.3	6.00	.4404	34.0	28.9
2.00	.1143	32.3	28.3	7.00	.518	34.1	28.9
2.10	.1236	32.5	28.4	8.00	.595	34.1	29.9
2.20	.1326	32.6	28.5	9.00	.671	34.2	29.0

TABLE 8.—Viscosimeter Comparisons—Factors to Reduce Engler Time to Saybolt Universal or Redwood Time

Engler time in seconds	Kinematic viscosity	Saybolt time / Engler time	Redwood time / Engler time	Engler time in seconds	Kinematic viscosity	Saybolt time / Engler time	Redwood time / Engler time
56	0.0155	0.578	0.535	130	0.1624	0.641	0.557
58	.0210	.581	.537	140	.1793	.645	.558
60	.0260	.585	.538	150	.1956	.649	.559
62	.0309	.588	.540	160	.2121	.652	.559
64	.0357	.592	.541	180	.2438	.654	.560
66	.0403	.595	.542	200	.2753	.656	.560
68	.0449	.598	.543	225	.3140	.658	.561
70	.0496	.601	.544	250	.3525	.659	.561
75	.0604	.605	.546	275	.3904	.660	.562
80	.0709	.611	.547	300	.4282	.661	.562
85	.0811	.616	.549	325	.4660	.662	.563
90	.0907	.621	.550	350	.5038	.663	.563
95	.1004	.625	.552	375	.5413	.664	.564
100	.1095	.629	.553	400	.5784	.665	.564
110	.1279	.633	.555	500	.7271	.666	.565
120	.1453	.637	.556	600	.8753	.667	.565

WASHINGTON, August 5, 1921.

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 211

[Part of Vol. 16]

RADIATORS FOR AIRCRAFT ENGINES

BY

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Bureau of Standards

MAY 26, 1922

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PREFACE

The material compiled in this treatise is based upon the war work and postwar work of the Bureau of Standards on the subject of aircraft radiators. Individual reports covering many phases of the subject have been published previously in the technical series of the National Advisory Committee for Aeronautics and in scientific and engineering journals. These reports, however, lack the systematic coordination, uniform terminology, and unified mathematical treatment which should characterize a handbook on the subject. Moreover, the problems which were investigated first because of their greater importance and which were the subjects of the reports published earliest are for that reason not so well covered as is now possible, because the later work threw much additional light upon matters not settled up to the time of publication of the early reports. Accordingly, the present paper is much more than a reprint of earlier reports, being a complete revision and recompilation of the material available.

The experimental work and the mathematical deductions included in the paper were contributed by a large number of members of the automotive power plants section of the Bureau during a period covering over three years, 1917–1920. The list of collaborators includes: H. C. Dickinson, W. S. James, S. R. Parsons, D. R. Harper 3d, W. B. Brown, R. V. Kleinschmidt, L. E. Voorhees, Lucinthia Butler, K. D. Wood, Jean Van de Water, F. D. Elmore, and Evelyn G. Haydock.

The program was arranged and the work carried forward under the general supervision of H. C. Dickinson and W. S. James. The mathematical deductions are largely by W. B. Brown. The earlier experimental work was done by R. V. Kleinschmidt and a corps of assistants, the latter part of the program being executed by the authors, who, with the assistance of Miss L. Butler, have revised and compiled all the material available into this paper.

Much of the success of the work was made possible by the cordial cooperation of the National Advisory Committee for Aeronautics, the Engineering Division of the Air Service, McCook Field, the Signal Corps, the Naval Aviation Service, several universities and research laboratories, the Society of Automotive Engineers, and the National Automobile Chamber of Commerce, and through these as well as independently many industrial radiator corporations. The latter cooperated most heartily in every way possible, furnishing test specimens and specially constructed cores, often at very considerable expense, communicating freely the advice of their engineers and the results of their own development departments and assisting in the dissemination of any information tending toward improved radiator design for aircraft. To all of the above grateful acknowledgment is rendered.

S. W. Stratton, *Director*
Bureau of Standards

January 14, 1922.

RADIATORS FOR AIRCRAFT ENGINES

By S. R. Parsons and D. R. Harper 3d

ABSTRACT

The characteristics which determine the value of the radiator in discharging its functions are considered in detail. Measurements of air flow through the core, of head resistance, of cooling power, and of geometrical characteristics are described and an exposition given of the relations between these and the conditions under which a radiator operates and its characteristics of form and construction. The work was based on special laboratory investigations, including laboratory tests of over 100 types of radiator core. A detailed record of the performance of these cores is included in the paper.

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I. INTRODUCTION

1. INTRODUCTION.—The function of a radiator for an aircraft engine is to maintain the temperature of the water in the cylinder jackets within a specified range, and the first requirement of the radiator is that it shall dissipate heat at a suitable rate. The necessary rate varies for a given engine and radiator as the power developed by the engine changes, while the capacity of the radiator for dissipating heat varies with the speed of flight, position on the aircraft, and the density and temperature of the air. The speed of the craft, and consequently the rate at which air passes through the radiator, is much greater for level flight at full power than for climb at maximum rate. Atmospheric temperatures vary widely between summer and winter and between low and high altitudes, and the density of the air falls off rapidly with altitude, being about one-half as great at 20 000 feet as at sea level. In general,

unless a supercharging engine is used,[1] the most severe conditions for the radiator are found when climbing at maximum rate near the ground in hot weather, when the engine is developing maximum power and both the speed of flight and the temperature difference between the air and the water in the radiator are low. Accordingly, the radiator is usually designed for this condition and provided with some means of shuttering to control its cooling capacity when under less severe conditions. But while capacity for dissipating heat is the first requirement, it is by no means the only one to be considered, for the radiator causes adverse effects on the aircraft which can not be overlooked. It adds somewhat to the weight of the structure, and it adds considerably to the air resistance and consequently to the power required to drive the craft. The conditions most favorable to heat transfer are, in general, such as to cause high air resistance, and the problems of design involve reconciling the antagonistic requirements of high heat transfer and low resistance.

Other factors, which must be considered by the designer but which will not be treated in detail in this paper, include such practical points as strength, ease of repair, and cost of production, and such adverse effects as obstruction of the pilot's view, modifications in the structure of the craft necessary to accommodate the radiator, and, in military machines, liability to injury from hostile fire.

The laws of surface friction for air flow and of heat transfer in long smooth tubes are fairly well known, but the aircraft radiator, which is usually a group of short and sometimes irregular tubes, presents a problem rather different from that of single long tubes, on account of end conditions. The points to be considered in the study of radiators may be grouped about three quantities—flow of air through the core of the radiator, head resistance, and rate of dissipation of heat.

The air flow evidently depends upon speed of flight; density of the air; geometrical form of the radiator; the position in which it is mounted and the effects of other parts of the aircraft, particularly the propeller; nature of the cooling surfaces; and effects of turbulence devices, if used. Head resistance depends upon all the factors mentioned for air flow, and may further be considered in two aspects: As the actual force on the radiator and as head

[1] If a supercharging engine is used, the most severe conditions for the radiator may be found at high altitudes.

resistance "chargeable to the radiator," which is the excess of resistance of the whole craft over what it might have been if no radiator had been required. Heat transfer evidently takes place in three stages—from water to metal, through the metal, and from metal to air—the third stage being the one that requires most careful consideration. The rate of heat transfer depends upon the rates and turbulence of water flow and air flow, temperature differences, nature of the cooling surfaces, and the geometrical form of the radiator.

From the above statements it will be seen that the performance of a radiator is *determined* by external conditions under which it operates and by its geometrical form and physical construction, and can be *represented* by what may be called its properties, such as air flow through the core, head resistance, and heat dissipation. The general excellence of a radiator will be denoted by a property called "figure of merit," which will be defined as the ratio [2] of the rate of dissipation of heat to the power absorbed in overcoming the head resistance and sustaining the weight.

The purpose of this report is to show the relations between the conditions under which the radiator operates, its characteristics of form and construction, and the properties that describe its performance, together with a detailed description of the experimental work on which the conclusions are based. The limitations of such a treatise in its immediate application, without any intervening step, to certain problems of design is the obvious one imposed by the impossibility of predicting for each possible case in actual practice the conditions which will determine the air flow. All of the work discussed in this paper and the results of the measurements recorded can be applied, provided only that the air flow through the core be known. The work of this investigation has been extended one step more, namely, to obtain results in terms of flying speed when the radiator is mounted in an unobstructed position. But for obstructed positions it is clear that the problem multiplies indefinitely, because there will be as many cases as there are differences of combination of position and shape of all the parts of an airplane in the path of the air stream through the radiator. Thus, it has proved impossible to do more for the reader who is interested in the performance of a nose radiator (the most common American position) than to set forth the relations to which reference is made at the beginning of this paragraph, leaving

[2] Both expressed in the same unit of power.

to him their application when he has secured a suitable measurement or estimate of the airflow characteristic of the particular nose installation with which he is concerned. The physical quantities used in the report have the following significance:

A. DEFINITIONS

2. CONDITIONS UNDER WHICH THE RADIATOR WORKS.—*Flying speed* will be taken as the speed of the aircraft relative to the air through which it is flying. Speed of flight relative to the earth would be meaningless in considering the radiator unless wind speeds were known. Unless otherwise stated, flying speed will be expressed in miles per hour (or meters per second).

Density of air will be expressed in pounds per cubic foot (or [3] kg/m^3).

Temperature differences between the air and the water in the radiator will be taken, for reasons explained below, as the difference in degrees between the average of the temperatures of the water on entering and leaving the radiator and the temperature of the air *at entrance*.

Altitude above sea level will be expressed in feet (or meters), and estimated atmospheric conditions at altitudes will be taken from Figs. 46–47, which are based on data given by W. R. Gregg in the Monthly Weather Review, January, 1918, for four stations in the United States.

The positions in which a radiator may be mounted on the aircraft will be divided into three classes—unobstructed, obstructed, and slip-stream positions.

Unobstructed positions are those in which the flow of air through and around the radiator is practically unaffected by other parts of the structure.

Obstructed positions are those in which the flow of air through the radiator is reduced by the effects of other parts of the structure.

Slip-stream positions are those in which the blast from the propeller blows over the radiator. They include, therefore, both positions which, but for the propeller, would be unobstructed and those which even in the absence of the propeller would be obstructed.

3. CHARACTERISTICS THAT IDENTIFY THE RADIATOR CORE.—The *core* of the radiator is that part through which air passes, as distinguished from the water tanks or headers. In order to elim-

[3] The same as $g/1000\ cm^3$.

inate size of radiator from the comparisons between types, all characteristics will be reduced to unit frontal area of core.[4]

Depth of core is the linear dimension in the direction of air flow and will be expressed in feet or in inches (or cm).

Length of core is the linear dimension in the general direction of water flow and will be expressed in feet (or cm).

Width of core is measured perpendicular to both length and depth and will be expressed in feet (or cm).

Direct cooling surface includes all surfaces backed by flowing water and from which heat is dissipated directly to the air. Cooling surface, whether direct or indirect, is usually expressed in square feet per square foot (or m^2 per m^2) of frontal area of core. In this form it is a ratio independent of the unit of area used, and in this paper it will be so expressed as a ratio.

Indirect cooling surface will be defined as any cooling surface not backed by flowing water. It may be formed by "fins" projecting into the air passages or by the walls of the water tubes at points where pockets are formed, so that the water is more or less stagnant. The important difference between direct and indirect cooling surface lies in the fact that as heat passes from the water to the air it is conducted in the case of direct cooling surface only through the thickness of the metal, while in the case of indirect cooling surface it must be conducted along the metal for a distance much greater than its thickness. Since this conduction is possible only when the temperature of the metal falls off with increasing distance from the source of heat, indirect cooling surface must have a lower mean temperature than direct surface adjacent to it.

Effectiveness of indirect cooling surface will be defined as the ratio of its rate of dissipation of heat to that of an equal area of direct surface under the same conditions of air flow, the direct surface being at a temperature equal to that of the parts of the indirect surface that are adjacent to its source of heat.

Free area is the ratio of the average total area of the cross section of the air passages to the frontal area of the core.

Weight of the core, either empty or including the contained water, will be expressed in pounds per square foot (or kg/m^2) of frontal area.

Water content is the weight of water contained in the core and will be expressed in pounds per square foot (or kg/m^2) of frontal area.

[4] Quantities so expressed may evidently be reduced to unit cooling surface if desired by dividing by the number of units of cooling surface in a section of core of unit frontal area.

Hydraulic radius of a water tube or of an air tube is the quotient of its cross sectional area by the perimeter of such a section and will be expressed in feet or inches (or cm).

4. Properties That Define the Performance of a Radiator.—The properties that indicate the performance of a radiator will be reduced to unit frontal area of core, and will be defined as follows:

Air flow or *mass flow* of air is the quantity rate of passage of air through the core and will be expressed in pounds per second per square foot (or kg/sec/m^2) of frontal area.

Air flow constant of a radiator or core is, for unobstructed positions, the fractional part of the air directly approaching the radiator or core that passes through it or unity minus the fraction deflected around it. For example, if the air has such a speed relative to the radiator as would deliver 10 pounds of air per second for each square foot of cross sectional area of the stream, but only 7 pounds per second pass through each square foot of core, while 3 pounds out of every 10 are deflected around it, then the air flow constant is 0.7. For obstructed and slip-stream positions the air flow constant is equal to the number of pounds of air flowing per second through a square foot of frontal area of core, divided by the product of the flying speed in feet per second and the density of the air in pounds per cubic foot.[5] The air flow constant is usually less than unity, although in slip-stream positions it may exceed that value.

The air flow constant is the factor m of the equation

$$M = m\rho S',$$

where M = air flow, lb./sec./ft.^{2} (or kg/sec./m^2).

m = air flow constant,

ρ = air density, lb./ft.^{3} (or kg/m^3),

S' = flying speed, ft./sec. (or m/sec.).

Head resistance of the core is the resistance that it offers to passage through the air and is equal to the force required to push it through the air at constant speed. Head resistance will be expressed in pounds per square foot (or kg/m^2) of frontal area.

Head resistance constant will be defined as the factor c' of the approximate equation

$$R' = c'\rho S'^2,$$

where R' = head resistance in poundals per square foot (or dynes per cm^2),

[5] Any other consistent set of units would serve equally well.

ρ = air density in pounds per cubic foot (or g/cm³),

S' = speed relative to the air[6] in feet per second (or cm/sec.).

Throughout this report head resistance has been reduced to an air density of 0.0750 pounds per cubic foot (1.204 kg/m³), and in most cases it will be convenient to use a constant called the "head resistance factor," which will be defined as the factor c of the approximate equation

$$R = c\,S^2,$$

where

R = head resistance in pounds per square foot (or kg/m²) frontal area at an air density of 0.0750 pound per cubic foot (1.204 kg/m³),

c = head resistance factor,

S = speed relative to the air, in miles per hour (or m/sec.).

It is evident that the numerical value of the "head resistance factor" will depend upon the units used.

Head resistance chargeable to the radiator is the difference between the resistance of the entire aircraft with its radiator (under given external conditions, such as speed and air density) and the resistance that it might have had if it could have been designed without a radiator. This includes the resistance of the core, the resistance of headers and exposed connecting pipes, and any increase in total resistance caused by mutual effects of the radiator and its surroundings, or by changes in the design of the structure necessitated by the presence of the radiator. For example, with engines of high power cooled by a radiator in the nose of the fuselage, the radiator may need to be so large in order to cool the engine as to require enlargement of the fuselage to contain it. When expressed numerically, head resistance chargeable to the radiator will be expressed in the same units as head resistance of the core, namely, pounds per square foot (or kg/m²) of frontal area of core.

Power absorbed by the core is the power used in overcoming its head resistance and sustaining its weight. It will be expressed in horsepower per square foot (or kw/m²) of frontal area.

Power absorbed chargeable to the radiator corresponds to head resistance chargeable to the radiator and is the difference between the power required to drive the aircraft under given external conditions, such as speed and air density, and the power that would have been needed if it could have been designed and operated

[6] Speed of the radiator relative to the air, which is the same as "flying speed" if the radiator is in an unobstructed position.

without a radiator. When it is expressed numerically, the unit used will be horsepower per square foot (or kw/m²) of frontal area *of core.*

Heat dissipation will be used as the term for rate of dissipation of heat by the radiator. Unless otherwise stated, it will be expressed in horsepower per square foot (or kw/m²) of frontal area of core, per 100° F (or 50° C) difference between the average of the temperatures of the water on entering and leaving the radiator and the temperature of the entering air.

Figure of merit is the ratio, when both are expressed in the same unit of power, of the heat dissipation to the power absorbed. The figure of merit of the core will then be the ratio of the heat dissipation to the power absorbed by the core, while the figure of merit of the radiator as a whole (which may or may not be equal to that of the core) will be the ratio of the heat dissipation to the power absorbed chargeable to the radiator.[7]

II. AIR FLOW THROUGH THE RADIATOR

5. General Statement.—The heat dissipated by a radiator is taken up by streams of air flowing through its tubes, and both the quantity of air delivered by the streams and their condition of turbulence are important factors in the dissipation of heat. Since air transmits heat only slowly by conduction, but principally by convection, the amount of heat taken from the metal surface depends very greatly on the number of different molecules of air that come in contact with the metal, and the most rapid transfer of heat requires a considerable scouring of the surface, while a layer of stagnant air acts as an effective insulator. But the collision of molecules of air with those of the metal, imparting heat to the air because of the molecular motion in the hot metal, also tends, because of the mass motion, to drag the air along with the radiator instead of allowing it to pass through the tubes; and while turbulence in the air streams facilitates heat transfer, it also increases surface friction, and thereby head resistance.

It is well known that at points not too near the ends in long tubes with smooth walls air flow is of two kinds, depending upon the relations between diameter of the tube and the speed, viscosity, and density of the air. At low speeds the flow is practically along

[7] This figure of merit must not be confused with the "figure of merit" used by the British, which refers to an arbitrarily chosen radiator as a standard, nor with that used by the French, which is the metric horsepower absorbed while dissipating heat at the rate of 1000 kilogram calories per minute. If the number 81.0 is divided by the French figure of merit, the quotient will be the figure of merit as used in this country for a temperature difference between air and water (as defined above) of 100° F.

stream lines parallel to the walls of the tubes and is called "viscous" or "stream-line" flow, while at higher speeds in the same tube the flow is broken up into vortices and is called "turbulent" flow. In viscous flow the surface friction or resistance to flow is due principally to the viscosity of the air and is roughly proportional to the first power of the speed, while in turbulent flow viscosity is of less importance than density, and the resistance is roughly proportional to the square of the speed. The shortness of the tubes of radiators and the irregular and broken forms often employed make it unsafe to apply the theory of long tubes except with considerable caution; but the qualitative ideas of viscous and turbulent flow are very helpful in visualizing the flow in the radiators, and it may be expected that in a cluster of tubes such as a radiator conditions corresponding to long tubes may be found much nearer the ends than in a single tube. Unless some kind of a mouthpiece is provided air coming over the edges of a single tube enters from many directions, and the same is true to some extent of radiator tubes that are near the edges of the section; but the air that enters tubes near the center of the section is confined by that entering the other tubes and is fairly well directed even before it reaches the tubes.

An investigation of the character of flow in the air tubes of the radiators indicated that turbulence exists, even in tubes with straight, smooth walls, and that in different types of radiator the turbulence varies considerably in nature or in degree. The experimental evidence was obtained from pressure gradients, surface cooling coefficients of radiators, cooling of wires in air streams, and temperature gradients across the air passages. Details of the method used and the results obtained are given in Appendix B.

The amount of air passing through the radiator tubes, which throughout this report will be understood to mean a mass flow rather than linear speed, is governed by the difference in pressure between the front and rear faces of the radiator, the speed of flight, the density of the air, and the geometrical characteristics of the tubes, and especially the ends of the tubes, which may have a considerable effect. In addition to these factors other parts of the structure in the vicinity of the radiator may greatly reduce the air flow by offering obstructions to the stream either in front of or behind the radiator. The effect of obstructions behind the radiator is often underestimated by the novice.

A. EXPERIMENTAL METHOD OF MEASURING AIR FLOW AND COMPUTATION

6. WIND TUNNELS.—Measurements of air speed were made by means of pitot tubes, each tube being compared with at least one other that was known to give readings correct within the limit of experimental errors. The wind tunnels in which the tests were made will be described in detail below, in the chapters on head resistance and heat transfer, while in this section only enough description will be given to explain the measurement of air flow. Three tunnels were used—one of square cross section, 8 inches (20.3 cm) on a side, the entire tunnel inclosed in a steel tank, another of square cross section, 8 inches on a side, but not inclosed, and a third of octagonal section, 54 inches (137 cm) between parallel sides. The steel tank could be closed and the air partially exhausted from it for tests at reduced pressure, and the (8-inch) tunnel inclosed in it will be called, for convenience in brief reference, the "reduced-pressure tunnel." In the uninclosed 8-inch tunnel superheated steam was provided as a source of heat for the calorimetric tests, and this tunnel will be called the "steam tunnel." Reference to the 54-inch tunnel will be made either by that name or as the "open tunnel," since the radiator section does not fill it, as it does the others, and the condition is similar to mounting in the open air.

(a) STEAM TUNNEL

7. APPARATUS.—Fig. 1 shows the form of section of radiator used for tests in the reduced pressure and steam tunnels. The core is 8 inches (20.3 cm) square, so that it just fills the air channel, while the water tanks or headers are outside of the air stream, and the mass flow of air through the core can be determined by measuring the flow past any section of the tunnel.[8] This measurement was made by means of a "pitot grid" and a piezometer ring, connected to a differential pressure gage, and indicated in Fig. 3. The pitot grid consisted of 16 dynamic pressure openings arranged at equal intervals in a plane, as shown in Fig. 4, and all connected to a single tube leading to the gage. The piezometer ring was constructed as follows: Sheet brass was inlaid in the walls of the tunnel for a distance of 25 cm (10 inches) before and behind the radiator in order to furnish a smooth surface. Square copper tubes were soldered to the outside of the brass sheets,

[8] If the linear speed of the air in the core of the radiator is desired, it can evidently be computed from the mass flow, the density, and the "free area" of the core.

around the perimeter of the section at which the dynamic openings of the grid were placed, which was 15 cm (6 inches) in front of the front face of the radiator, and holes about 0.5 mm (0.02 inch) in diameter were drilled from the outside through the tube and the sheet at intervals of 1.3 cm (0.5 inch) around the channel. The burr was scraped off from the inner surface, the holes cleaned and smoothed with a hand drill, and then the holes in the outer side of the copper tube were closed with solder. Similar piezometer rings were placed at sections 2.5 cm (1 inch) in front of and 2.5 and 15 cm (1 and 6 inches) behind the radiator for the measurement of differences in static pressure in the air stream passing through the radiator.

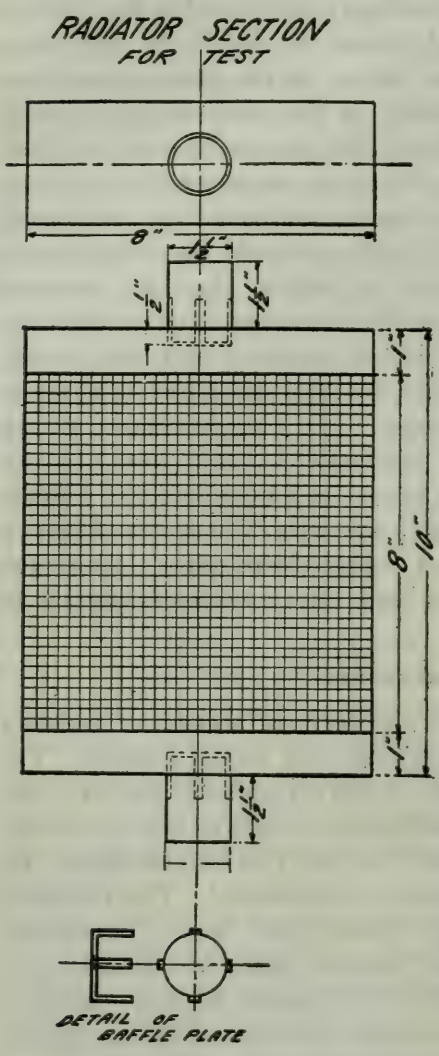


FIG. 1.—*Radiator section prepared for calorimetric test*

This arrangement is the one used for measuring air flow during calorimetric tests. For the work with a secondary velocity gage, denominated the "pressure tube" (art. 15), an additional section of tunnel was inserted, bringing the dynamic pressure openings of the front pitot grid 36 cm (14 inches) from the face of the radiator.

8. CALIBRATIONS.—The pitot grid and its piezometer ring were calibrated, and the distribution of speed across the channel was determined by comparison with a movable pitot-static tube placed at different positions over the section. Simultaneous readings were taken of the movable pitot-static tube and the grid. The mean speed in the channel was computed with the aid of Simpson's rule from the readings of the movable tube and was compared

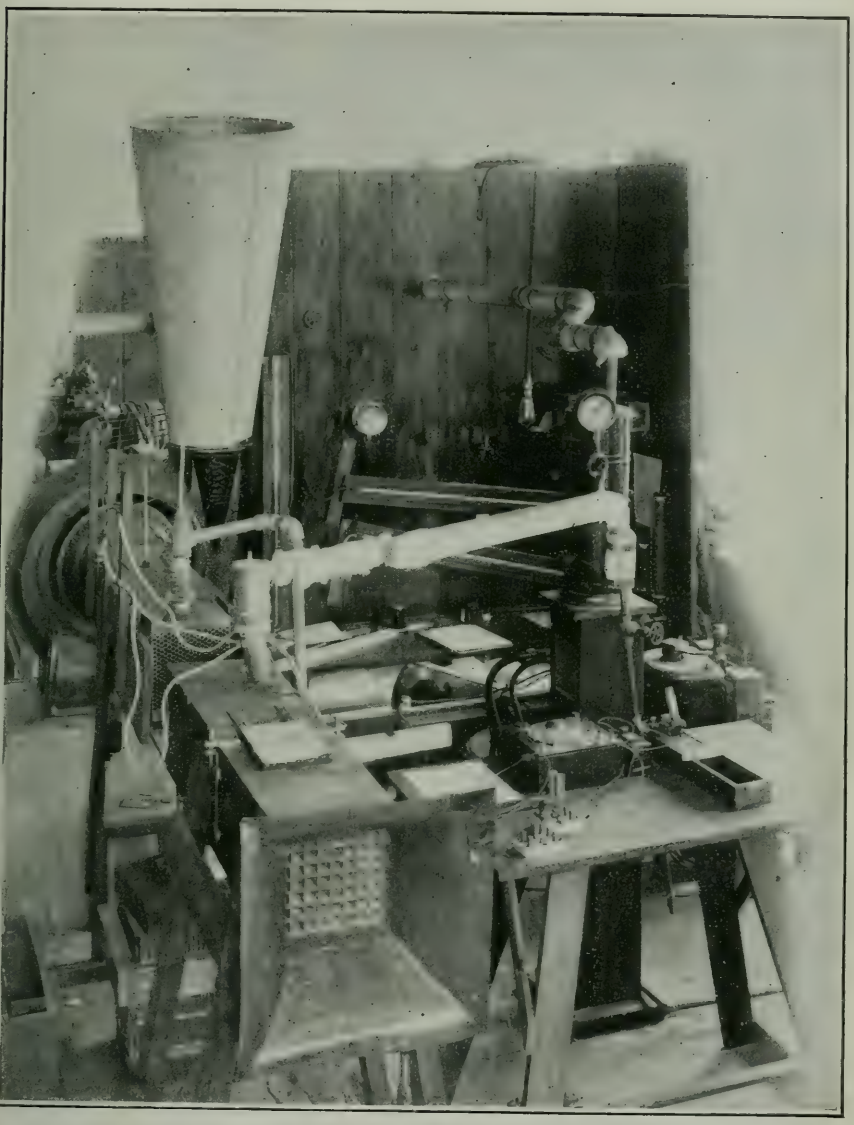


FIG. 2.—*Small wind tunnel 20 cm (8 in.) square and accessory apparatus for calorimetric tests of radiator cores*

Test core with hexagonal cells is shown at the opening near the center of the tunnel. Hot water or steam connections furnish the heat supply

with the readings of the grid and piezometer ring. The steam tunnel was used in two forms. When first built, air was pushed through it by a blower, but after a time it became necessary to move the apparatus to another building, and it was then rebuilt as a suction tunnel. The explorations in the first tunnel showed that at seven different speeds covering the range of experimental use the indications of the grid were within about 1.5 per cent of the mean air speed, the errors being greatest at the lower speeds, at which the readings were least reliable. In the rebuilt tunnel the exploration was less satisfactory, for the movable pitot tube was only about 12 cm (5 inches) behind the grid, and its readings were

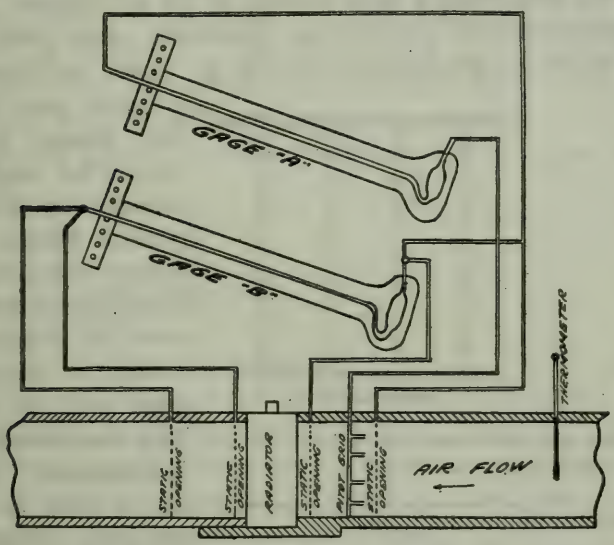


FIG. 3.—*Schematic diagram of calorimetric wind tunnel ("steam tunnel"), 20 cm (8 in.) square*

Used for heat transfer measurements at wind speeds up to 30 meters per second (68 miles per hour)

affected by the crossbars of the latter, but since the same grid was used and the conditions for uniform velocity distribution appeared better than in the first tunnel it seemed unnecessary to make an exploration at some other section, which would have involved cutting an opening in the wall. The correctness of the readings of the pitot grid and piezometer ring was established by the agreement between values of heat dissipation computed from the rate of flow and rise in temperature of the air and from the rate of flow and fall in temperature of the water during regular calorimetric tests.

A further indication of the straightness of flow in the channel was obtained by the use of ammonium chloride smoke introduced

into the tunnel through a glass tube about 8 mm ($\frac{5}{16}$ inch) in diameter, which projected through the bell mouth of the tunnel to a few centimeters beyond the straightening honeycomb at its entrance. On looking into the tunnel, either down stream through the mouth or across the stream through a window in the top, the smoke was seen to follow a straight course down the stream, with very little spreading for some distance. When a radiator was placed in the tunnel, the smoke was found deposited over a certain area of the face, which was fairly well defined, rather than shading off very gradually. At a distance of 1 meter from the mouth of the smoke tube the areas ranged from 4 to 9 per cent of the cross section of the tunnel, indicating a slow mixing of the air stream.

9. OBSERVATIONS.—Differential pressures were read on two inclined water gauges indicated in Fig. 3. Each was hinged about a point near the bulb. The gauges were calibrated for each angular position by direct comparison with a vertical U-tube containing a light oil of known density. In order to determine the density of the air at the pitot grid, its temperature was measured on a thermometer about 60 cm (2 feet) in front of the grid. Pressure was determined by the reading of a barometer in the room, corrected by the amount of the rise or fall of pressure between the room and the piezometer ring (measured on one of the inclined gauges by connecting one side to the ring and leaving the other side open), and approximate relative humidity was read on a recording hygrometer. The errors in humidity were sometimes as high as 10 or 15 per cent, but the effect of humidity enters the computations only as a very minor correction, and even errors of 15 per cent in humidity measurement may safely be neglected.

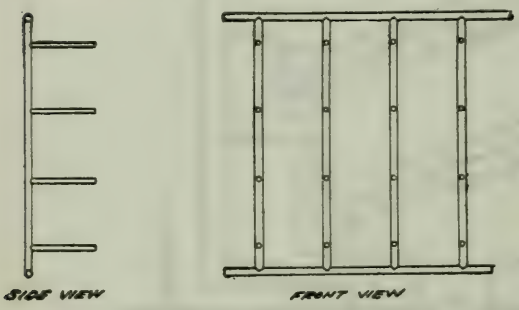


FIG. 4.—*Pitot grid for the measurement of air velocity in the small wind tunnel ("steam tunnel")*

Transmits to a water gage the average dynamic pressure at 16 points in the cross section 20 cm (8 in.) square

10. COMPUTATION.—For the computation of air flow the equation of the pitot tube

$$v = \sqrt{2gh}$$

was put in the form

$$M = c\sqrt{x\rho},$$

where v = linear air speed,
g = acceleration of gravity,
h = "head" of air (units of length),
ρ = density of air,
M = air flow,[9]
x = reading on the gage,
c = a conversion factor, depending upon the units used and the calibration of the gage.

The density of the air was computed by either of two methods. In the first method the pressure and temperature were converted to pounds per square inch and degrees Fahrenheit, and density was taken from a chart given by W. C. Rowse,[10] which includes correction for humidity. This chart could not be used, however, for low pressures, and the following method for use with the reduced pressure tunnel was also used with the steam tunnel.

The density of dry air may evidently be obtained from the equation

$$\rho_d = \frac{bp}{T},$$

where ρ_d = density of dry air,
p = pressure,
T = absolute temperature,
b = a constant, depending upon the units used.

Also considering any constant temperature T, let
p = atmospheric pressure,
p_d = partial pressure of air (dry)
p_v = partial pressure of water vapor,
p_s = pressure of saturated water vapor at temperature T,
ρ = density of mixture,
ρ_d = density of dry air at pressure p, and temperature T,
ρ_a = density of dry air at pressure p_d and temperature T,
ρ_v = density of vapor at p_v and T,
ρ_s = density of saturated vapor at temperature T,
r = relative humidity,
c = correction for humidity such that,

$$\rho = \rho_d + c. \tag{1}$$

From Dalton's law

$$p = p_d + p_v, \tag{2}$$

[9] It is important to bear in mind that, unless otherwise stated, air flow has in every case been reduced to unit time and unit frontal area of core.

[10] Transactions, Amer. Soc. of Mech. Engs., 1913, p. 690.

and from the definitions of density and relative humidity

$$\rho = \rho_a + r\rho_s, \tag{3}$$

while by Boyle's law

$$\rho_a = \rho_d \frac{p_d}{p}, \tag{4}$$

also

$$p_v = rp_s. \tag{5}$$

Substituting equations (4) in (3) and (5) in (2),

$$\rho = \rho_d \frac{p_d}{p} + r\rho_s, \tag{6}$$

$$p = p_d + rp_s. \tag{7}$$

Equations (1), (6), and (7) contain the three unknown quantities ρ, p_d, and c. Solving for c,

$$c = r\left(\rho_s - \rho_d \frac{p_s}{p}\right). \tag{8}$$

The quantity in parentheses in equation (8) is a function of the temperature only, and for convenience in computation a chart (Fig. 5) was made showing this quantity as a function of the temperature.

(*b*) REDUCED PRESSURE TUNNEL

11. APPARATUS.—Figure 6 shows a diagram of the reduced pressure tunnel, which, in the sections adjoining the radiator, was similar to the steam tunnel. At first a Thomas meter was used to measure the air flow, but the velocity distribution was poor, and at high air speeds the meter gave large errors and was finally discarded. In its place a pitot grid and piezometer rings were used, similar to those described above for the steam tunnel. With the addition of honeycombs to straighten the flow, the pitot grid and its piezometer ring were found by an exploration similar to that made in the steam tunnel to indicate speed correctly within 1.5 per cent at all speeds used.

For the measurement of pressure a barometer was connected directly to the piezometer ring corresponding to the pitot grid. Temperature of the air in the channel was measured by an electric resistance thermometer of No. 40 nickel wire (diameter 0.08 mm, 3 mils) inclosed in 0.5 mm (0.02 inch) copper tube and constructed in the form shown in Fig. 7. The thermometer and the Wheatstone bridge used to read it were calibrated by the appropriate sections of the Bureau, and the measurement of temperature could be made to 0.2° C.

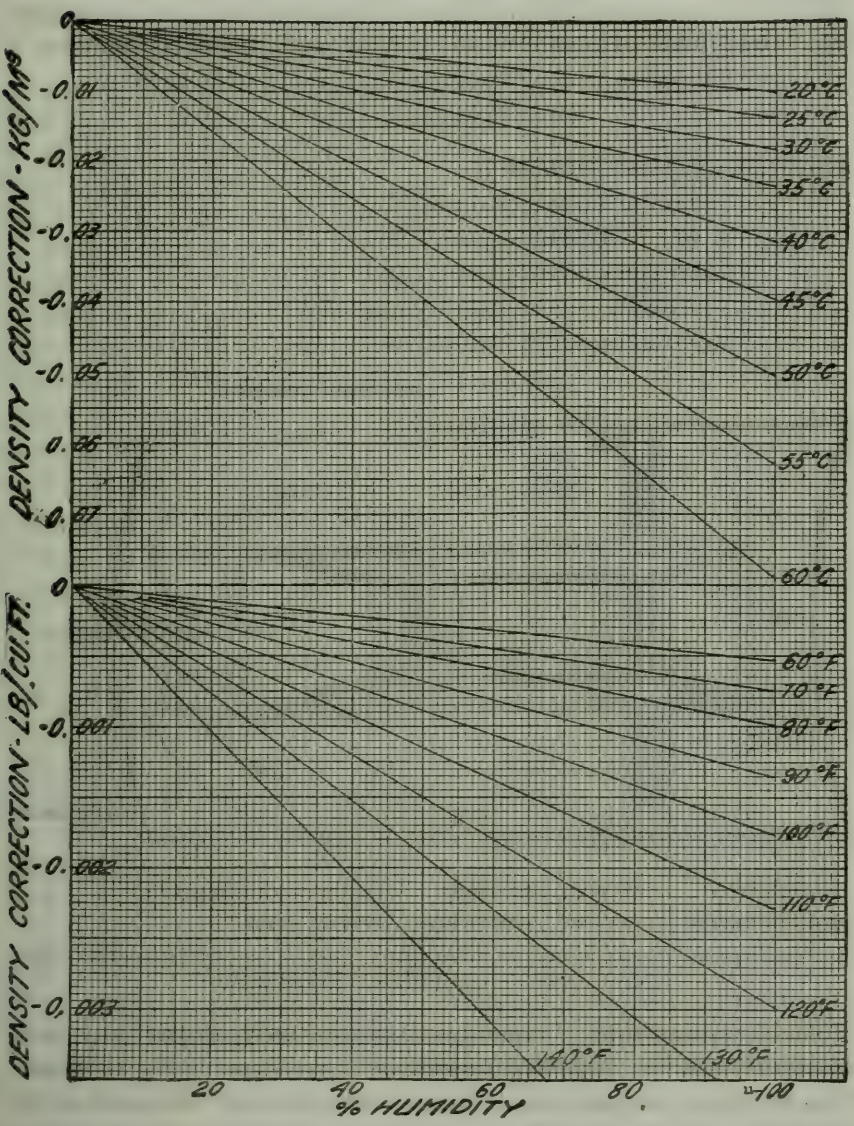


FIG. 5.—*Correction term to be added (negatively) to the density of dry air at 760 mm barometric pressure and given temperature in order to obtain the density of humid air at various humidities*

12. HUMIDITY.—Relative humidity was determined from the readings of a wet-and-dry bulb hygrometer inside of the tank containing the tunnel by means of an ordinary chart for the purpose. At reduced pressures the readings of the chart required correction which was made by means of an equation given by W. H. Carrier.[11]

$$r = \frac{e'}{e_2} - \frac{(P - e')\ (t - t')}{(2800 - 1.3\ t) e_2}$$

where r = relative humidity,
t = dry bulb temperature, °F,
t' = wet bulb temperature, °F,
e' = pressure of saturated vapor at t' °F,
e_2 = pressure of saturated vapor at t °F,
P = pressure of air and vapor.

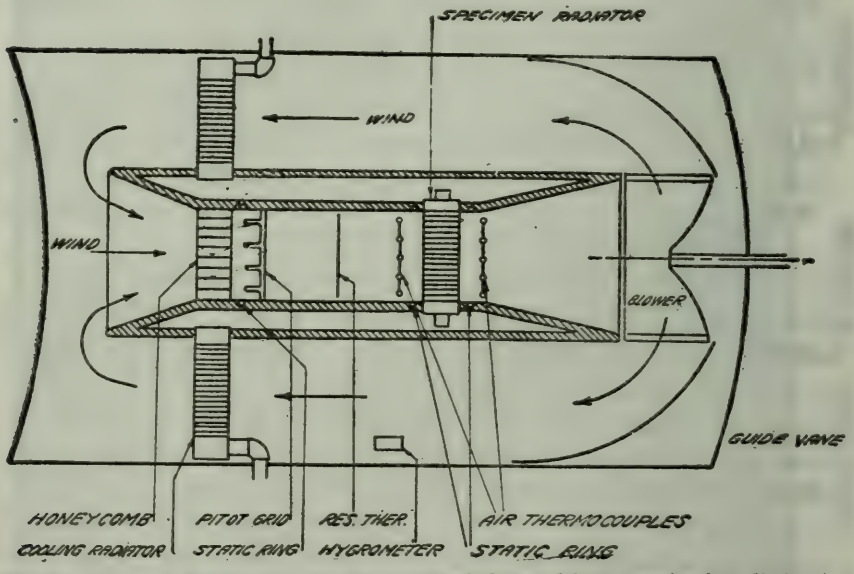


FIG. 6.—*Schematic diagram of reduced pressure wind tunnel for measuring heat dissipation under conditions simulating high altitude flight*

The pressures enter the formula as ratios only, so that any unit whatever may be employed so long as it it the same for all three. The remaining factors, temperature terms, are not independent of the choice of units, the 2800 and 1.3 being correct for the Fahrenheit scale. The formula was converted into units convenient for the present use, and the factor

$$\frac{t - t'}{(2800 - 1.3\ t)\ e_2}$$

[11] Transactions, Amer. Soc. of Mech. Engs., 1911, p. 1020.

was plotted as a function of t and $(t-t')$ for convenience in computation. Having determined pressure, temperature, and humidity, the density of the air was computed as described for the steam tunnel.

(c) OPEN TUNNEL

13. APPARATUS.—The measurement of air flow in the 54-inch (137 cm) open wind tunnel presented quite a different problem from that of the 8-inch closed tunnels. In this tunnel the problem was to determine the flow through the core of the radiator in terms of the linear speed of the air stream in which it was placed.

The wind tunnel is illustrated in Figs. 8 and 9. Explorations across the working section showed that when the channel was unobstructed the velocity was uniform to about 1 per cent at all points not nearer than 20 cm (8 inches) to the wall. The speed of the air stream was measured by a pitot-static tube mounted in the center of the channel at a point about 180 cm (6 feet) in front of the radiator. The mounting of the pitot tube was a hollow brass strut of cross section about 22 mm (7/8 inch) in length and 9 mm (3/8 inch) in maximum width, rising from the floor of the tunnel and containing the tubes that led to the differential pressure gage. The radiator was mounted on a support rising through the floor of the tunnel, described in detail in the chapter (III) on head resistance (art. 27).

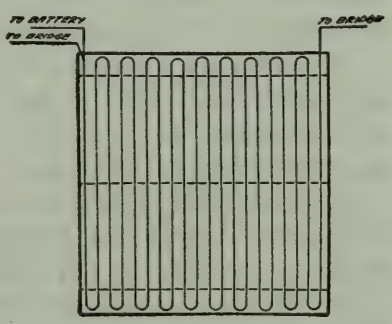


FIG. 7.—*Resistance thermometer (electric) for measurement of air temperature in wind tunnel*

Nickel wire, 0.08 mm in diameter, is incased in a copper tube, wound as shown to integrate temperature over the whole cross sectional area of the wind tunnel

To test whether the conditions truly represent a speed in the open air, silk threads were attached to a fine vertical wire strung about 15 cm (6 inches) in front of a large-size section of high head resistance, G–3, 40.6 cm (16 inches) square. The threads showed a considerable curvature of the stream lines around and close to the section, but no appreciable curvature within 20 cm (8 inches) of the tunnel wall. It was assumed, therefore, that the effect of the radiator on the air stream was confined well within the section of the tunnel, and that open-air conditions were well represented.

14. METHOD OF MEASUREMENT.—The measurement of air flow through the core presented some difficulties, and a number of methods were tried before one was found that gave results at all reliable.

(*a*) An attempt was made to measure the flow with a small pitot-static tube behind the core and in positions ranging from well within the cell to a few inches behind the core, but it soon became evident that this method was not practicable because of the turbulence of the air encountered.

(*b*) Threads were attached to the rear face of the radiator to define the stream, in the hope that the air passing through the core could be followed to a position where the flow would not be too turbulent for the use of a pitot-static tube, and that in such a position it would be possible to measure the speed and the area of cross-section of the air that had passed through the core. It was found, however, that even aside from the difficulty introduced by the tendency of the pull on the threads to straighten them, so that they would not follow the lines of the stream, the flapping of the threads was too great, and consequently their position too indefinite to allow of measurement of the area included by them.

(*c*) A hot-wire anemometer was tried and gave some promise of fair results, but before it had been thoroughly tested, a simpler method seemed to be giving very fair results, and the use of the anemometer was discontinued.

(*d*) A method that was used in a large number of cases employed a specially constructed venturi meter, of which a longitudinal section is shown in Fig. 11. Its use is described below.

(*e*) The most satisfactory method used was based on a small tube, which will be called the "pressure tube," stretched through the air passages of the radiators, with a small static pressure opening near its center. This has been used on all cores that present straight air passages, while the air venturi is still the most satisfactory instrument that has been used on cores through which the pressure tube can not be passed.

15. PRESSURE TUBE.—The pressure tube was used in both the steam tunnel (8-inch, 20.3 cm) and the open tunnel (54-inch, 137 cm), and its purpose was to furnish a basis of comparison between observations in the two tunnels. Its use is based on the assumption that if air flows through the radiator at a definite rate certain definite pressure differences will be set up in the air passages, whether the radiator is in the steam tunnel, where the flow of air through it is measured, or in the open tunnel, where the speed measured corresponds to speed of flight. In other words, the assumption is made that pressure drop between any two points in an air tube, due to the air current flowing in that tube, is a definite function of the current strength, although not necessarily

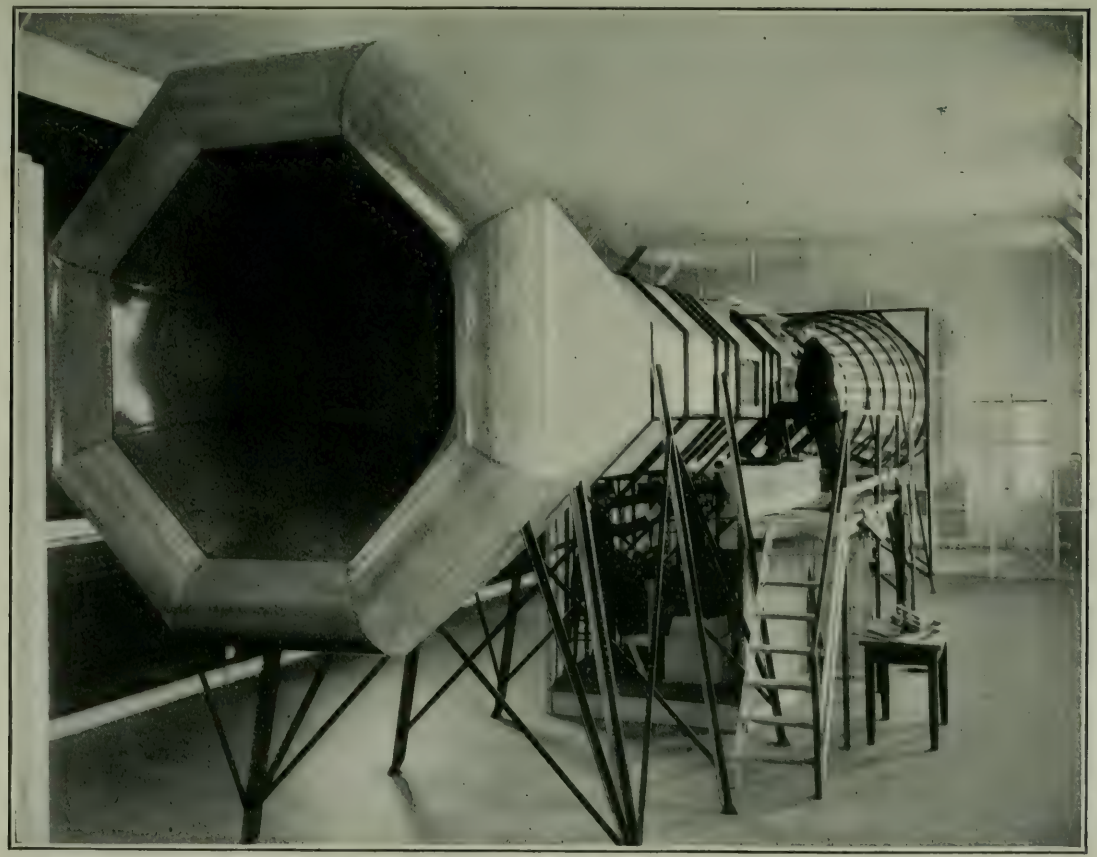


FIG. 8.—*Large wind tunnel, octagonal section 137 cm (54 in.) in diameter*

Used for measurements of air flow through radiator cores for flying speeds up to 30 meters per second (68 miles per hour); for head resistance measurements, etc.

a known function and is single valued, so that whenever a given pressure drop is obtained it is because the same current is flowing in the tube. Operating on this principle, the pressure tube will identify in the core of the radiator when mounted in the open tunnel an air flow of which the numerical value is ascertainable from absolute measurements in the closed (steam) tunnel. This air flow in the core can then be compared with the air flow in the open tunnel at a distance from the radiator and the relation obtained between flying speed and air flow in the core.

The pressure tube was of steel, about 1 mm (0.04 inch) outside diameter, 61 cm (24 inches) long, and, as stated above, contained an opening near the center, the plane of this opening being parallel to the air flow, so as to measure static pressure without any com-

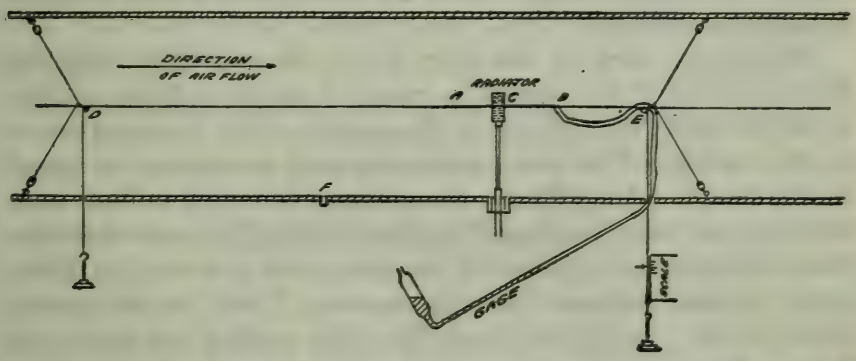


FIG. 9.—*Schematic digram of the method of mounting the "pressure tube" through a radiator cell in the large open wind tunnel*

ponent of velocity head. The forward (upstream) end was closed and the rear end was connected to larger tubes leading to one side of an inclined water gauge. The other side of the gage was left open to the pressure in the room.

The manner of mounting the pressure tube in the 54-inch wind tunnel is indicated in Fig. 9. The tube AB with the static opening at C, was strung through one of the air passages of the radiator and suported by fine wires of hard-drawn brass running over pulleys D and E, 3.1 cm (1.2 inches) in diameter and held taut by weights. As the tube was moved forward or backward the position of the static pressure opening was indicated by a pointer on the wire traveling over a scale S. The pulleys D and E were supported by fine wires, and turnbuckles near the tunnel walls provided a convenient means of adjusting their position. The only important detail in which the mounting in the steam tunnel

differed from that in the open tunnel was that instead of using wires to support the pulleys *D* and *E*, cross bars of brass 9.5 mm (3/8 inch) in diameter were used to support grooved rings 19 mm (3/4 inch) in diameter over which the wires ran. Before taking readings in either tunnel the tube was set so that either the static pressure opening or a point at a known distance from it was at one face of the radiator and the corresponding position of the pointer was noted.

16. OBSERVATIONS.—The method of observation was to obtain some desired air speed in the wind tunnel and holding that speed as nearly constant as possible, to measure its value and read simultaneously the differential pressure on the gage connected to the pressure tube with the opening *C* in different positions, covering a range from somewhat in front of the front face to a short distance behind the rear face.

Preliminary work in the open tunnel showed that when the forward pulley *D* was placed far enough from the radiator, so that it did not affect the readings of the pressure tube, it caused errors in the readings of the pitot-static tube used to measure air speed in the tunnel. Accordingly, the pressure tube and pulleys were removed and with a radiator in place a comparison was made between the speed as indicated by the pitot-static tube and the differential pressure between the static opening *F* and the air outside of the tunnel. In the later tests this static opening was connected both to the gage of the pressure tube and to a second gage the other end of which was open to the air, the pitot-static tube was removed from the tunnel, and speed was computed from the readings of the second gage. Readings with the pressure tube in different cells of the radiators showed that the air flow through the cells increased slightly (1 per cent) near free edges over that at the center of the section and decreases somewhat (4 per cent) near a side to which a header is attached. These variations are so slight, however, and effect such a small portion of the section that for practical purposes the flow may be regarded as uniform over the face. Slight differences in adjacent tubes, however, make it necessary in most radiators to use the same air cell for comparison in both the steam and open tunnels. The pressure tube was used in the center of an air cell, and it was found by trial that readings could be duplicated if the tube was centered with reasonable care.

Three quantities are measured—position of the opening *C* with reference to the radiator, air speed, and pressure difference. The

position is probably correct to about 0.2 mm (0.01 inch) and the air speed is probably within 2 per cent. The greatest error in the pressure difference is probably due to the fact that on account of the shortness of the steam tunnel the forward crossbar is only 77 cm (30 inches) in front of the radiator and may have some effect on the velocity distribution over the face. The total error, however, is believed to be within 7 per cent, while comparisons between different radiators are probably good within 2 per cent.

The assumption in article 15 that pressure differences within the air tubes are the same in either tunnel for a given flow of air through the tubes is supported by the following facts: (1) In cores that have smooth, round air cells (Figs. 145 and 146) a smooth constant gradient is set up about 2 or 3 cm from the front face and continues to a point 1 or 2 cm from the rear face. (2) This gradient is the same at the same velocity in cores of different depths, as Table 1 shows.

TABLE 1.—Pressure Gradients as Functions of Depth of Radiator Air Tubes

Tube diameter		Radiator depth		Pressure gradient
cm	Inches	cm	Inches	
0.51	0.36	12.7	5	0.66
.91	.36	20	8	.67
.91	.36	25	10	.66
.76	.30	10	4	.84
.74	.29	20	8	.85

Both these facts indicate that the gradient set up does not depend on conditions outside the radiator tubes or, in other words, that the end effects die out very speedily.

17. COMPUTATION.—It was found that to a first approximation the observed pressure differences were proportional to the square of the air flow, and this relation was used to correct for fluctuations in the speed during a test.

The direct result of one set of observations was a curve such as that of Fig. 10, in which pressure readings are plotted against positions in the air tube. If all these curves had been straight lines through the center portion of the radiators, their slopes could have been determined and used to measure the air flow. But since many were quite irregular the following more general method was used.

Selecting from Fig. 10 a part of the curve ABC well within the radiator, such that B is midway between A and C (along the X-axis), let

M = air flow through the whole core,
x = distance of any point from rear face,
x_0 = abscissa of A,
x_1 = abscissa of B,
x_2 = abscissa of C,
p = pressure at any point,
m = air flow constant,
M_0 = unobstructed air flow in open tunnel,
ρ = air density,
S = air speed in open tunnel.

By "unobstructed air flow," M_0, is meant the mass of air that would flow in unit time across unit sectional area of the open tunnel if the radiator were not there. Also, let the mean pressure between A and B and between B and C be represented by P_1 and P_2, defined by the equations

$$P_1 = \frac{\int_A^B p dx}{x_1 - x_0} \tag{1}$$

$$P_2 = \frac{\int_B^C p dx}{x_2 - x_1} \tag{2}$$

and let $Q = P_2 - P_1$.

The air flow constant m is by definition

$$m = \frac{M}{M_0}. \tag{3}$$

For long straight tubes Q varies over a considerable range [12] as $\rho^{n-1}S^n$, and the same relation has been found to be true in the short tubes of the radiators. A number of radiators were used in the steam tunnel at three or more speeds, and the power of the air flow to which the pressure difference Q was proportional is shown in Table 2. The exponent computed from the Lees formula for long tubes of such diameters and at such speeds as are found in radiators was 1.73, and that value has been used throughout the computations of air flow constant.

[12] Lees, proceedings, Royal Soc. of London, A-91, 1914, p. 46.

TABLE 2.—Exponent of Air Flow to Which Pressure Drop in the Air Tubes is Proportional

Radiator No.	Type	Exponent n	Radiator No.	Type	Exponent n
A-7	Square cell	1.6	B-17	Hexagonal cell	1.7
A-9	do	1.7	C-2	Pseudo circular cell	1.7
A-14	Square cell, irregular	1.7	C-12	True circular cell	1.8
A-19	Square cell, walls swaged	1.8	C-13	do	1.7
A-29	Square cell	1.8	D-1	Irregular	1.6
A-31	do	1.9	D-2	do	1.9
B-3	Hexagonal-pseudo cellular	1.8	D-3	do	1.5
B-13	do	1.6			

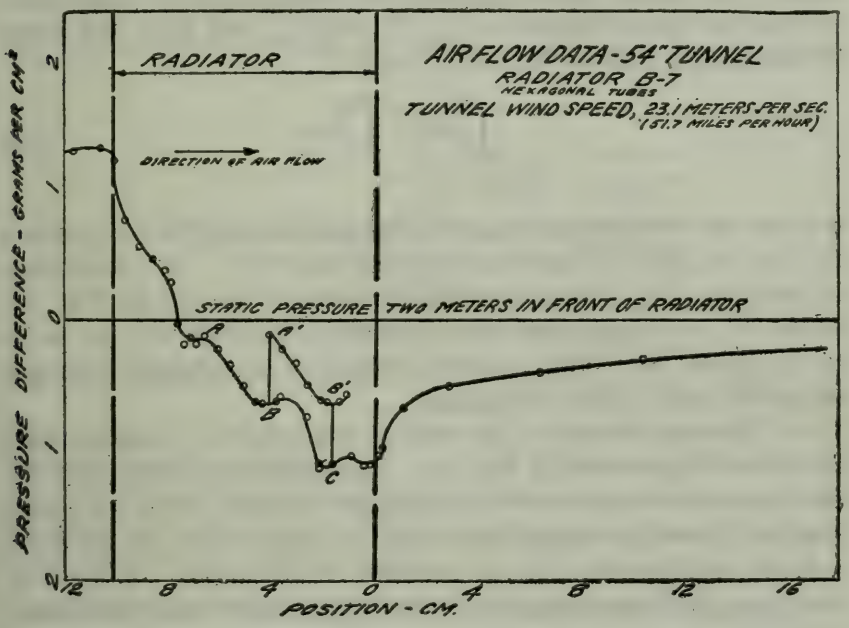


FIG. 10.—*Pressure drop in the air tube of a radiator with irregular shaped cells*

The displaced segment of the curve A′ B′ is for measurement of air flow under conditions where the pressure gradient is not linear with distance along the tube axis. Method explained in Art. 17

The pressure difference Q may be expressed by the equation

$$Q = b'\rho^{n-1}S^n \tag{4}$$

which, since

$$M = \rho S \tag{5}$$

may be written

$$Q = b'\frac{M^n}{\rho}. \tag{6}$$

But the density was nearly the same in both tunnels, and the small differences existing were negligible in the result.[13] The

[13] See Appendix C.

density was accordingly combined with the constant b' and equation (6) written

$$Q = bM^n. \tag{7}$$

In the closed tunnel Q and M were measured at three or more speeds and a mean value of b obtained. In the open tunnel

$$M = \left(\frac{Q}{b}\right)^{\frac{1}{n}} \tag{8}$$

and

$$M_o = cS, \tag{9}$$

where c = a factor depending upon the density and the units used.

Now, by the definitions of Q, P_1, and P_2, and since the point B was chosen midway between A and C,

$$Q = \frac{\int_B^C p\,dx - \int_A^B p\,dx}{x_1 - x_0} \tag{10}$$

and the air flow constant may be obtained directly from equations (3), (9), (8), and (10) and the observed value of b. The numerator of equation (10) is measured by the area $A'\ B'\ CB$ of Fig. 10, where $A'\ B'$ is the curve AB displaced a distance $(x_1 - x_0)$ so as to fall above AB. This area was plotted on an enlarged scale and measured with a polar planimeter.

18. VENTURI METER.—The venturi meter used for measurement of air flow is illustrated in Fig. 11. The cylindrical throat and the two cones were made from sheet copper soldered, with the joints filed into curves of stream-line form. A copper tube led out from a single small needle hole in the side of the throat. A piece of sheet iron bent into cylindrical form was soldered over the cones, extending from in front of the front cone nearly to the rear end and covering the central contracted portion which otherwise would cause considerable resistance to the air stream. A second needle hole in front of the front cone was connected to a small tube which ran back along the outer surface, turning up where it reached the tube coming from the throat. The instrument was 25 cm (10 inches) long, with a mouth 3.5 cm (1⅜) inches in diameter. Three soft iron wires soldered to the sides of the instrument were passed through cells of the radiator and bent over in front to hold it in place on the rear face. The pressure difference was measured on an inclined water gage.

The meter was attached to the rear face of a radiator placed in the steam tunnel and a relation found between the pressure differ-

ence reading of the meter and the air flow through the core. It was then used similarly on the same radiator in the open tunnel and a relation found between its pressure difference and the tunnel speed (corresponding to flying speed). From these two relations air flow in the core was determined in terms of flying speed, on the assumption that the venturi pressure difference was the same in both tunnels for a given air flow through the core. The method evidently amounts to a calibration of the meter with each radiator on which it was used, but was necessary because the meter readings in the steam tunnel varied with different radiators for the same air flow.

In a few cases the air flow constant was determined both with the venturi meter and with the pressure tube, and a fair agreement

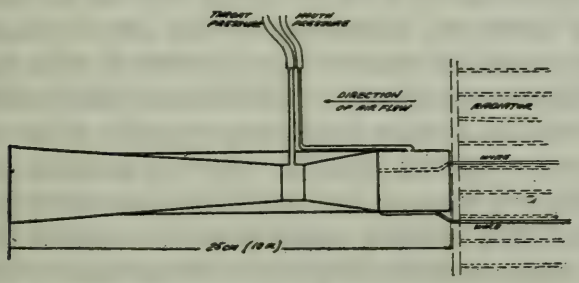


FIG. 11.—*Venturi meter for comparison of air flows through the core of a radiator under various conditions*

between the two instruments is indicated in Table 3. Throughout this paper the constant determined by the use of the pressure tube has been used wherever possible for computations, since that seems to be more reliable than the other.

TABLE 3.—Air Flow Constants by Venturi Meter and by Pressure Tube

Radiator No.	By venturi	By pressure tube	Radiator No.	By venturi	By pressure tube
A-6	0.59	0.53	B-8	0.52	0.44
A-13	.55	.57	C-1	.45	.43
A-21	.51	.48	C-4	.62	.50
A-23	.51	.49	C-7	.60	.61
B-1	.71	.68			

B. AIR FLOW FOR UNOBSTRUCTED POSITIONS OF RADIATOR

19. SPEED AND DENSITY.—With the possible exception of certain types of radiator mentioned in the next paragraph, the air flow through the core is proportional to the speed of flight and to the density of the air when unaffected by other parts of the craft

on which the radiator is mounted; i. e., when the radiator is in an unobstructed position. This relation may be expressed by the equation

$$M = m \rho S',$$

where

M = air flow, mass per unit time per unit frontal area,
ρ = density,
S' = flying speed,
m = "air flow constant."

If consistent units are chosen for M, ρ, and S', the constant m will be dimensionless and is, as stated above (art. 4), the fractional part of the air directly approaching the core that passes through it, or unity minus the fraction deflected around it.

In the experimental work the linear relation between air flow and flying speed was established by the use of the air venturi meter, and it seemed unnecessary to verify it with the pressure tube. Apparent exceptions to this relation were found for cores so constructed as to cause a whistling sound in an air stream and for one type, G–4, with irregular sided air passages which carry the air obliquely through the core. For the whistling types the venturi gave very irregular curves of air flow against flying speed, and while the instrument is hardly reliable enough to warrant very much confidence in the curves, it is probable that some irregularity exists, because the curves of head resistance against flying speed also show unusual form (art. 38). For the type G–4 the venturi gave a linear relation over the range 8 to 33 m per sec (15 to 75 miles per hour), but the line if produced would have indicated zero air flow at about 3.5 m per sec (8 miles per hour). But little confidence should be placed in the measurement of air flow in this type or in the whistling types.

20. Empirical Equation for Air Flow Constant.—The air flow constant m is a function of the geometrical form of the radiator and of the nature of the cooling surfaces, and for the more common types ranges from 0.4 to 0.7 and has been found as low as 0.3. Its values for about 80 types of core are given in Table 21. The air flow constant may be expected to be a function of the "free area," the depth, and the hydraulic radius of the air tubes. Since m is dimensionless, the depth and the hydraulic radius, each having the dimension of a length, must enter the function as a ratio, and m may be of the form

$$m = f\left(a, \frac{r}{x}\right)$$

Also $m = 0$ when $a = 0$, and when $r = 0$
and $m = 1$ when $a = 1$ and $x = 0$
where a = free area of radiator,
x = depth of radiator,
r = hydraulic radius of air tubes.

These conditions are satisfied and the experimental values fairly well represented by the empirical equation

$$m = a\left(1 - 10^{-k\frac{r}{x}}\right) \qquad (1)$$

where k is a constant. If the constant k is computed from measurements on a particular type of core, the equation may be used for a good estimate of air flow through a similar type of different depth, and a fair estimate may be made for any ordinary type of cellular core by using a value of 44 for k. The degree to which this value represents actual values is indicated in Table 4, which compares observed air flow constants with those computed by means of the equation using $k = 44$. The value of k depends to some extent upon the form of the air tubes, including the ends of the tubes, and upon the smoothness of the surface, but does not vary very widely for the different types tested. The equation is of proper form to represent such conditions as that the air flow increases with increase in free area and in hydraulic radius of air passages, and decreases with increase in depth, which adds to the frictional resistance.

21. Nature of Air-Tube Walls.—The air flow is, of course, greater when the cooling surfaces are smooth than when they are of the same dimensions but rough, though the surfaces commonly found in well-made radiators do not differ enough in smoothness to show any marked effect. The section C–8, circular tubes with hexagonal ends, as received from the manufacturer had very rough surfaces, and its air flow was estimated from measurements with the venturi meter both as received and after the tubes had been somewhat smoothed. The difference in nature of the surfaces resulted in an increase of 5 per cent in the air flow, but this increase is greater than would ordinarily be obtained by polishing the tubes of a radiator, because the original surface was unusually rough. For large air flow the walls of the air passages should be not only smooth but straight. Projections, indentations, and holes in the walls cause additional resistance and thereby reduce the air flow.

75013°—22——3

TABLE 4.—Comparison of Observed Air Flow Constants With Values Computed from Empirical Relation $m=a\,(1-10^{-44\,r/x})$

Radiator No.	Free area (a)	Hydraulic radius (r)	Depth (x)	Air flow constant	
				Computed (m)	Observed (m)
	Ratio	cm	cm		
A-1	65.5	0.127	7.5	0.54	0.56
A-2	65.7	.127	9.9	.48	.43
A-3	79.6	.160	6.1	.74	.56
A-4	76.5	.198	7.3	.71	.62
A-5	68.0	.142	7.6	.58	.54
A-6	74.9	.155	10.0	.59	.53
A-7	64.2	.127	12.3	.43	.47
A-8	66.2	.132	6.0	.60	.56
A-9	66.8	.132	7.2	.56	.56
A-13	70.4	.140	8.5	.57	.57
A-15	53.0	.119	7.5	.42	.41
A-16	69.8	.157	7.6	.61	.57
A-17	72.1	.157	10.2	.57	.56
A-19	67.7	.130	7.6	.56	.53
A-20	66.9	.127	12.7	.43	.44
A-21	65.6	.160	7.5	.58	.60
A-22	66.6	.160	10.1	.53	.54
A-23	68.5	.162	12.7	.49	.49
A-25	67.1	.130	10.2	.49	.50
A-33	63.4	.130	9.8	.46	.54
B-1	83.6	.223	6.4	.81	.68
B-5	81.2	.180	5.2	.79	.62
B-7	77.0	.176	10.2	.63	.52
B-8	73.3	.175	13.4	.54	.44
B-10	65.1	.163	6.4	.60	.60
B-11	65.1	.163	7.6	.58	.57
B-12	65.1	.163	8.3	.56	.58
B-13	65.1	.163	10.2	.52	.51
B-15	65.2	.183	10.1	.55	.54
B-17	65.2	.155	9.5	.53	.60
C-1	51.9	.140	8.6	.42	.43
C-2	60.4	.272	21.2	.44	.45
C-4	62.6	.158	7.4	.55	.50
C-6	70.9	.188	7.6	.65	.56
C-8	60.0	.226	12.8	.52	.59
C-9	61.1	.188	10.2	.54	.57
C-10	57.9	.185	10.2	.52	.57
C-11	60.6	.190	10.2	.52	.55
C-12	59.8	.228	25.3	.36	.42
C-13	65.3	.228	20.2	.45	.46
C-14	64.3	.183	20.2	.39	.38

22. YAW.—The effect of yawing the radiator or turning it so that the air strikes it at some other angle than normal to its face is to decrease the flow of air. No quantitative relation between angle of yaw and decrease in air flow can be given, however, because of the lack of reliable measurements, and the effect is doubtless considerably greater with some types of core than with others.

C. AIR FLOW FOR OBSTRUCTED AND SLIP-STREAM POSITIONS

Only a very limited study has been made of obstructed and slip-stream positions because of experimental difficulties and the lack of facilities for tests on full-size airplanes, and the results of

the experimental work for such positions must be regarded as qualitative only.

23. Nose of the Fuselage.—In order to study the properties of a radiator mounted in the nose of a fuselage, a rough model of a fuselage was constructed. The model (illustrated in Figs. 12 and 13) was about 1.5 m (60 inches) long, 25 cm (10 inches) wide, and 33 cm (13 inches) high, and was made to accommodate a 20 cm (8 inch) square section of core in the front, which could also be covered by a detachable stream-line nose. Two rectangular openings, each about 3.8 by 16.5 cm (1½ by 6½ inches), were cut in each side of the body, a little behind the position of the radiator, and were fitted with adjustable sliding doors, which allowed some control of the amount of air passing through the radiator. The model was mounted in the 54-inch wind tunnel in the same manner as a radiator, and the air venturi meter was attached to the radiator inside of the body. The values obtained for the air flow constant were as follows, the normal air flow constant (for unobstructed positions) being given for comparison:

TABLE 5.—Estimated Air Flow Constants, Radiator in Nose of Fuselage

[The figures given are those obtained in measurements made with a model shaped like a fuselage but much smaller and without engine, etc.]

Radiator No.	Type	Vents closed	Vents open	Unobstructed position
A-23	Square cell	0.15	0.36	0.49
B-1	Hexagonal, pseudocellular	.15	.38	.68
G-3	Spiral vanes	.15	.32	.37

The great reduction in air flow constant furnishes a good illustration of the effect of obstruction in the air stream behind the radiator. Although in actual airplanes louvres on the sides of the fuselage may tend toward an increase in air flow, the model contained nothing corresponding to the engine which offers a considerable obstruction to air flow in actual installations.

It may be stated that, in general, the air flow through a radiator in the nose of a fuselage is much less than for the same type of core in an unobstructed position, and it appears likely that for common types of core mounted in the nose the air flow constant falls between 0.1 and 0.4, or perhaps 0.5, depending upon the type of core, the obstructions behind the radiator, and the facilities provided for letting the air out of the fuselage.

24. Wing Position.—While the air flow through a radiator in the nose of a fuselage is low, it is probably much lower through

a radiator mounted in the wing, so that its faces conform approximately to the upper and lower surfaces of the wing. For a rough estimate of air flow a half-size section of wing was used, 66 by 107 cm (26 inches wide by 42 inches deep), of the U. S. Navy X type, with the fabric cut away to accommodate a section of radiator. The radiator core was 25 by 41 cm (10 by 16 inches), with 8 mm ($\frac{5}{16}$ inch) square tubes 8.5 cm ($3\frac{1}{2}$ inches) long, sloping at an angle of 45° upward and to the rear. The wing and radiator were mounted in the 54-inch wind tunnel in such a way that the angle of attack could be set at will.

Because of the change in direction of the air stream both on entering the radiator and on emerging from it the usual methods could not be used for measuring air flow and an estimate was made by the following method: One of the air tubes near the center of the core was plugged with putty, and two small copper tubes with dynamic pressure openings were placed inside of the plugged tube, facing the plug from opposite sides of the core. Readings were taken of the pressure difference between these dynamic openings and of the speed of the stream in the tunnel, and in order to show the meaning of the readings an ordinary square cell radiator of the same diameter and length of cell was used in a similar manner in the steam tunnel, where the air flow through it could be measured. By this means a relation was found between the air flow and the pressure difference obtained by the opposed dynamic pressure openings in the plugged tube. The estimated air flow constants obtained by this method were as follows:

TABLE 6.—Estimated Air Flow Constants in Wing Radiator

Angle of attack	Air flow constant
2° 15′	0.16
4°	.18
8° 15′	.26

For unobstructed position, constant=0.55

25. Slip-Stream Positions.—If the blast from the propeller blows over the radiator, the air flow is increased by an amount that depends upon the distance from the propeller, the position along a radius of the slip stream, and the "slip coefficient" of the propeller. Many designers assume that the relative speed of the air is greater in the slip stream than out of it by a definite amount, and the figures assumed for the increase range from 10 to 25 per cent, but such an assumption can not be generally true.

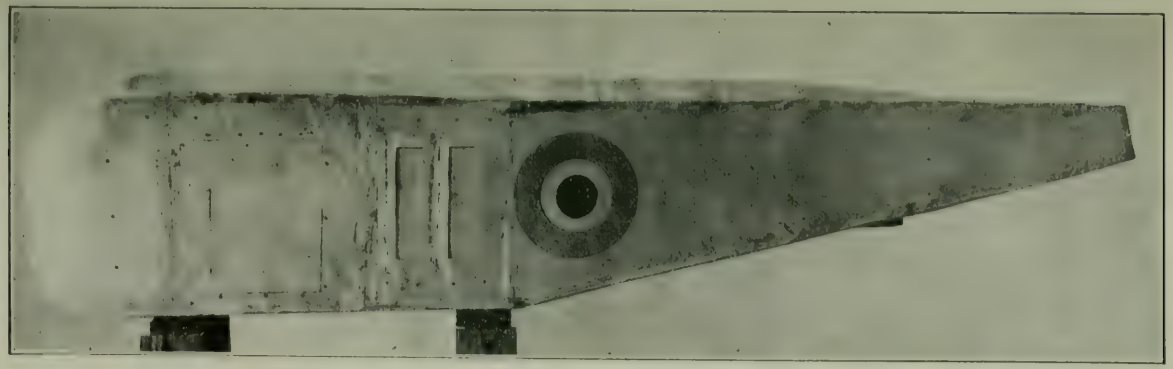


FIG. 12.—*Model airplane fuselage with crudely streamlined nose*

Used to measure relative head resistance for comparison with conditions shown in Fig. 13. This view shows relative proportions of the fuselage

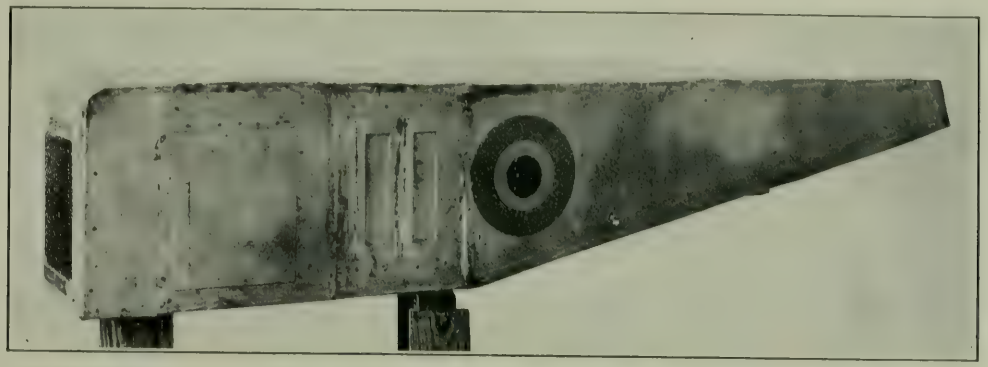


FIG. 13.—*Model airplane fuselage with nose radiator replacing streamlined casing*

Same as Fig. 12, foreshortened. Variable area vents, shuttered by sliding doors, permit a range of variation of the air flow

If, however, the relative air speed is, for example, 20 per cent greater in a certain part of the slip stream than out of it, the air flow through a radiator in such a position will not be 20 per cent greater than it would be but for the effect of the pro eller because of the swirl in the slip stream, which makes the air strike the radiator at an angle with its face, and is equivalent to yawing the radiator or turning it through an angle.[14]

III. HEAD RESISTANCE AND POWER ABSORBED

26. General Statement.—The head resistance of a radiator is closely related to the air flow through it, for the factors which cause high resistance also cause the air flow to be low. The general trend of the relation between head resistance and air flow is indicated by the line on Fig. 14, which shows head resistance factor in terms of air flow constant. The scattering of the points is probably due largely to differences in form of the ends of the air tubes.

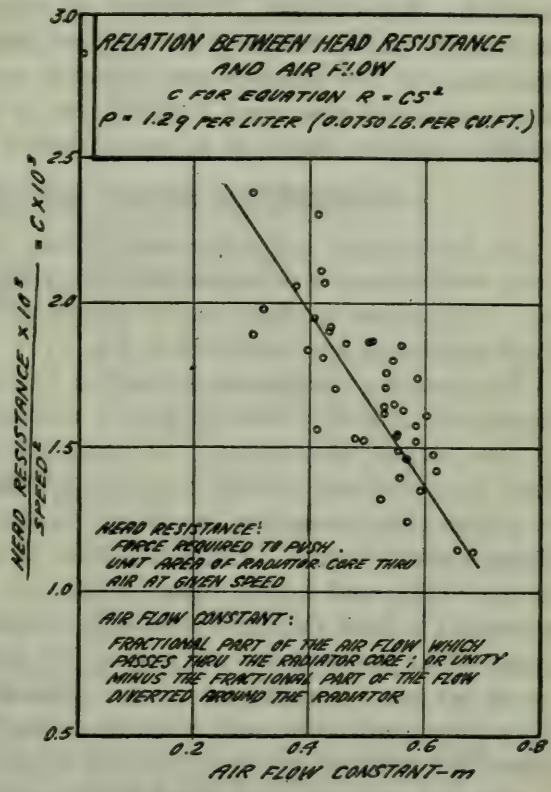


Fig. 14.—*Relation between head resistance of a section of radiator core and air flow through the core*

Shows the larger head resistance for radiators of design such as to pass but a small fraction of the air stream through the core, deflecting the major fraction around the radiator

Since some air passes through the radiator and some is deflected around it, the effect of flow through tubes is combined with the effect of a solid body in an air stream, and the head resistance is accordingly made up of two parts, one due to actual surface friction on the walls of the air passages and the other to the action of the radiator in dis-

[14] For a discussion of effects of the slip stream the reader is referred to Technical Report No. 71 of the National Advisory Committee for Aeronautics, "Slip-Stream Corrections in Performance Computation."

turbing the flow of air. The second part corresponds to the resistance of solid bodies and is usually accompanied by eddies in the air stream. For convenience this kind of resistance will be called "eddy resistance." Eddy resistance is found not only at the entrance and exit of the air passages, but at any points where there are projections, indentations, or holes, in the air-tube walls.

If the radiator is in an obstructed position, it may so modify the flow of air around other parts of the craft on which it is mounted as to increase the total resistance of the craft by an amount considerably greater than its own resistance when in an unobstructed position. For example, if instead of using a fuselage with a stream-line nose, the nose is flat and contains a radiator, the resistance of the fuselage and radiator may be greater than if the stream-line nose were retained and a radiator of equivalent cooling capacity placed in an unobstructed position.

A. EXPERIMENTAL METHOD AND COMPUTATION

27. APPARATUS.—Head resistance was measured in the large open wind tunnel of octagonal section 54 inches (137 cm) in diameter. The tunnel is illustrated in Fig. 8 and the balance on which head resistance was measured in Fig. 15.

The entering air passes through a honeycomb of sheet-metal hexagonal cells of about 75 mm (3 inches) diameter and 30 cm (1 foot) depth, then through a straight section about 7.6 m (25 feet) long, and out through a conical diffuser, at the end of which is a four-blade propeller fan driven by a 55 kw (75 horsepower) direct-current motor. The motor may be operated on either 120 or 240 volts, and further speed control is obtained by means of rheostats in both field and armature circuits, giving a continuous range of air speeds from 7 m per sec. (15 miles per hour) to about 40 m per sec. (90 miles per hour). The air speed was measured by a pitot-static tube, and when the tunnel was unobstructed the speed was uniform across the section to about 1 per cent.

The balance on which head resistance was measured is illustrated diagrammatically in Fig. 15. It consists essentially of a bell crank suspended by thin flexible steel strips (safety razor blades). An adjustable counterpoise balances the weight of the horizontal arm, while heavy weights just above the damping vane lower the center of gravity enough to insure stability when using a heavy section for test. The vertical arm supporting the section is extensible and is fitted at the top with a detachable brass block,

which is screwed to a plate not more than 3 mm (⅛ inch) thick, soldered to the lower side of the radiator.

The balance measures the amount of the head resistance, and in order to compute the actual force exerted on the radiator it is necessary to know the ratio of the distances from the fulcrum to the point on the horizontal arm where the weights are hung and to the center of pressure on the radiator. Since it was not convenient to measure these distances with accuracy, their ratio was checked by a calibration of the balance, made by applying known

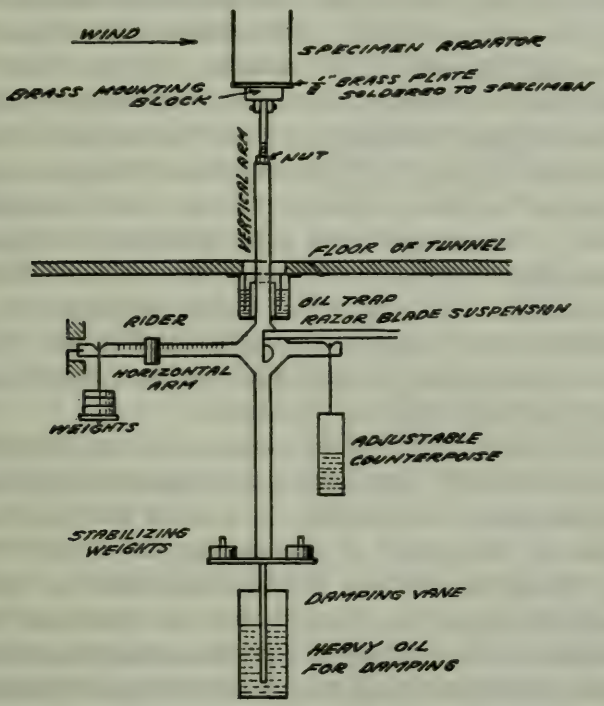


FIG. 15.—*Aerodynamic balance for measurement of head resistance of a section of radiator core mounted in large wind tunnel*

horizontal forces to the vertical arm. Readings were taken with the vertical arm extended to three different lengths.

Preliminary investigations showed that ordinary radiators as manufactured are sufficiently uniform that the center of pressure of a section of core may be assumed to lie at the geometrical center, and that the resistance is the same with either face presented to the wind. (This is not true of certain special types whose front and rear faces are not similar.) As stated above (art. 13), the disturbance of the air stream by the radiator seemed

to be confined well within the section of the tunnel, so that open-air conditions were well represented.

28. OBSERVATIONS.—The method of taking readings was as follows: The radiator (bare core, without headers) was mounted on the vertical arm of the balance and the distance measured from its center to a fixed point on the arm. The distance from this point to the fulcrum was determined by the calibration mentioned above. To determine the position when the radiator was normal to the air stream (no yaw), a section was set at various angles, the position of minimum head resistance assumed to represent zero yaw and a reference point marked on the tunnel wall by sighting across the face of the radiator. It was found that the alignment could be obtained equally well by sighting through the tubes of the section at the honeycomb at the entrance of the tunnel. For yawed runs the angle of yaw was measured approximately by sighting across the front of the section at a scale mounted on the tunnel wall. The air speed was quite sensitive to changes in the line voltage applied to the motor which drove the propeller, and it was necessary for two observers to take simultaneous readings on the balance and the gage of the pitot-static tube. There was, however, very little lag between the two instruments, and very satisfactory readings could be obtained.

29. COMPUTATION.—The head resistance of the radiator and the support is obtained by multiplying the apparent force, as read on the horizontal arm of the balance, by a factor which depends upon the distance of the center of pressure on the radiator from the fulcrum. When the vertical arm was extended to such length which made this factor 0.5, the radiator was quite near the center of the channel, and for ordinary tests this setting was used. With test sections of different sizes this procedure required the exposure of different lengths of the supporting arm to the air stream.

To correct for the resistance of the supporting arm, its resistance was measured at various speeds when extended to three different lengths, and a quantity corresponding to the length used was subtracted from the apparent resistance of the radiator as read on the balance. Because of the mutual effect of the radiator and its support the resistance of the combination is probably not exactly equal to the sum of the resistance of the parts when alone and the procedure doubtless introduces a small error. Since, however, the correction for the supporting arm was usually but 7 to 12 per cent of the resistance of the radiator, the errors in this

correction are probably well within the limit set by other conditions in the experimental work.

Head resistance was expressed in pounds and reduced to 1 square foot frontal area and to a "standard" air density of 0.0750 pounds per cubic foot (1.204 kg/m³). For this reduction it was assumed, in accordance with aerodynamic practice and the results of observations on pressure drop through radiator sections in the closed tunnels, that head resistance is proportional to density. The tests showed that the resistance varies roughly as the square of the speed, and within the range of sizes used the resistance per unit frontal area (which is the meaning of the term "resistance" as used throughout this report) is not appreciably affected by size or shape. The departure of the resistance from variation as the square of the speed is indicated in Table 8 (art. 35). The effect of size and shape is shown in Fig. 16. The sizes used ranged from 20 cm by 20 cm (8 by 8 inches) to 40 cm by 40 cm (16 by 16 inches) and 30 cm by 60 cm (12 by 24 inches).

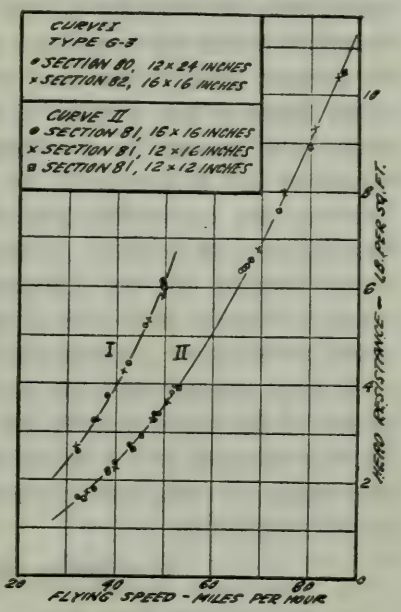


FIG. 16.—*Head resistance per unit area of sections of core differing in shape and size but otherwise exactly alike. No variation with size discernible*

30. REDUCTION FOR AIR DENSITY.—The reduction of head resistance to the value it would have in air of standard density may be accomplished by merely substituting standard for actual density in the computation of air speed, because a change in density has similar effects upon the resistance of the radiator and upon the pressure difference impressed on the pitot tube used to measure the air speed. If

R = head resistance per unit area,
S = speed of the air stream,
ρ = air density,
x = differential pressure of the pitot tube,
a, b, b' = constants,

the resistance is given by an equation of the form

$$R = a\,\rho\,S^2, \tag{1}$$

and the equation of the pitot tube

$$S = b'\sqrt{\frac{x}{\rho}} \tag{2}$$

may be put in the similar form

$$x = b\,\rho\,S^2. \tag{3}$$

From these equations it will be evident that if during the observations the density is, for example, 2 per cent greater than standard, both the resistance R and the pressure difference x will be greater by a factor 1.02 than they would have been for the same speed if the density had been standard; but while the resistance is greater by the factor 1.02, the speed computed from equation (2) is increased by a factor $\sqrt{1.02}$, and the relation between the quantities actually measured, namely, R and x, is independent of density. Thus, the use of standard rather than actual density for the computation of speed, results in giving a value for speed such that if the density had been standard this speed would have corresponded to the observed resistance.

If, as is usually the case, the resistance is proportional to some power of the speed slightly less than 2, a small error is introduced by this method, but a study of its effects has shown that within the range of variations encountered in work with radiators the error is negligible.

B. SURFACE FRICTION IN AIR TUBES

31. Radiators Not Similar to Long Tubes.—The laws of surface friction in long circular tubes have been studied by many investigators, and the formula of C. H. Lees [15] represents the facts over a very wide range of diameters of tubes and of speed, density, and viscosity of fluid, but only for a middle part of the tube, so far from the ends that end effects may be neglected. Of the exact behavior of air at the ends of the tubes, however, and of the energy transformations involved at the ends much less is known. The minimum distance from either end of a tube at which many investigators would have confidence in measurements of static pressure is considerably greater than the total length of ordinary radiator tubes, and the laws of flow in long tubes can be applied to radiators only with great caution. Nevertheless, it should be borne in mind that in a cluster of tubes such as a radiator conditions correspond-

[15] Proceedings, Royal Soc. of London, A–91, 1914, p. 46.

ing to long tubes may be found much nearer the ends than in a single tube. The very divergent flow lines characteristic of entrance and exit for a single tube are doubtless found true for tubes near the edge of a radiator, but except near the edges it is likely that the mutual interactions of the multitude of streams must necessarily result in more nearly parallel flow lines even before entering the tubes. A further caution in applying deductions from flow in long, circular tubes is to bear in mind that while some radiators are constructed with circular air tubes of fairly smooth walls others have square, hexagonal, elliptical, and irregular shaped cells, while the "fin and tube" types can not be said to have air tubes, and many of the so-called cellular types do not have true air tubes but merely "passages" more or less cut up by projecting strips of metal, known as "fins." Variations in surface friction are also indicated by differences in kind or degree of turbulence in different radiators (Appendix B).

Figs. 138 to 152, showing pressure in the air tubes as indicated by the pressure tube used in measuring air flow, give some indication of the effects of surface friction and of the relations between surface friction and total head resistance; i. e., surface friction plus "eddy resistances" at the faces of the radiator. The plots show clearly the contraction of the jets of air on entering the tubes and their expansion after leaving the radiator, and the differences in form of the curves give some qualitative indication of the behavior of the air at the ends of the tubes, though measurement of static pressure is difficult under such conditions and great significance should not be attached to the exact form of the curves drawn.

32. Comparison of Pressure Gradients in Radiators With Values for Long Tubes.—In view of the preceding statements, it is hardly to be expected that a simple relation would be found between the surface friction in ordinary radiator tubes, their dimensions, and the speed and other properties of the air; nor is it surprising that in the case of types with circular cells, in which a pressure gradient may be measured by the use of the pressure tube, this gradient should not agree closely with that computed by means of the Lees [16] formula. The gradients meas-

[16] The Lees formula is as follows, absolute units in any consistent system being used throughout:

$$R_f = \rho v^2 \left[0.0765 \left(\frac{\mu}{\rho v D} \right)^{0.35} + 0.0009 \right],$$

where R_f = surface friction, absolute units of force, per unit surface,
ρ = fluid density,
v = linear velocity of fluid,
D = diameter of tube,
μ = viscosity of fluid.

ured in five radiators of circular tube types were found to exceed those computed by the formula for similar conditions by the amounts shown in Table 7.

TABLE 7.—Excess of Observed Over Computed Pressure Gradients in Air Tubes

Radiator No.	Excess
	Per cent
C-8	8
C-11	19
C-12	30
C-13	31
C-14	25

But, although the observed values of surface friction were higher than those computed by the formula, the powers of the air flow to which the friction is proportional agree fairly well with the formula, as is shown by Table 1 (art. 17).

33. Condition of Surface.—The effect of roughness of surface is to increase surface friction, but the surfaces usually found in radiators do not differ enough in roughness to show any very marked effect. This effect was studied by two methods—by measuring the pressure gradient in a single brass tube with different conditions of surface, and by comparison of the gradients obtained with the pressure tube in two radiators whose air tubes were of nearly the same form and dimensions but with quite different conditions of surface.

The single tube was 105 cm (41.3 inches) in length, with an inside diameter of 0.95 cm (3/8 inch). Small holes were drilled in it at 10 cm intervals, beginning 5 cm from each end, and tubes were attached to give static pressure at each of these 11 positions. Since it was necessary to remove the burr from the inside of the tube after the holes were drilled, the original surface was not used, and the first measurements were made with the tube somewhat polished. Other measurements were made with the surface oiled lightly, smoked lightly, and roughened somewhat. The air flow was measured by a special Thomas meter made for the purpose. Although it was not calibrated for lack of convenient apparatus, the meter was made with some care, and was doubtless good at least for comparative purposes. Pressure gradients were obtained by plotting the pressures read at the 11 static-pressure holes against their respective positions and were expressed in grams per square centimeter per centimeter length of tube. The

observations on the smoothed and oiled surfaces were very consistent, but when the tube was smoked or roughened they were less consistent, probably because of effects of the smoking and roughening on the static-pressure openings. The errors due to these irregularities, however, do not exceed 3 per cent. Corrections for the effect of changing density of the air were of the order of 1 per cent and were neglected.

No differences in pressure gradient obtained with the different surfaces were found to be outside the probable limit of experimental error, with the possible exception of the smoked surface, which would probably have shown a greater difference if the tube had been more thoroughly smoked. The length and small diameter of the tube made roughening the surface somewhat inconvenient, and the pressure gradient would, without doubt, have been considerably increased had the surface been made considerably more rough, this being indicated by the results of measurements in a tube of a radiator. The results obtained are shown in Fig. 17.

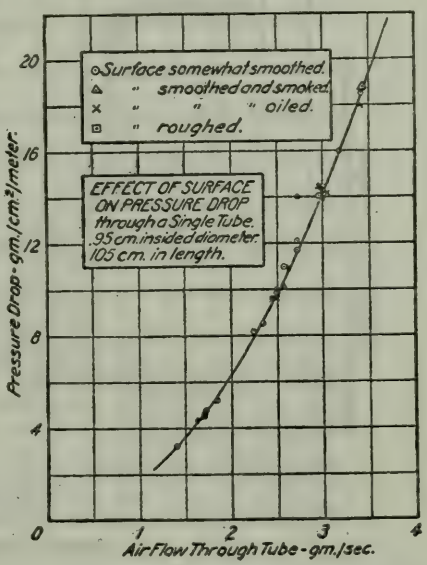


FIG. 17.—*Effect of condition of surface of an air tube on surface friction.*

Four different conditions of surface with all other factors constant show no significant differences in pressure gradient

The two radiators used for comparison were the sections C–9 and C–10, which were very nearly alike except that the tubes of C–10 were very rough, while those of C–9, though originally in the same condition, had been somewhat smoothed. Observations were made at three rates of air flow, two of which are shown in Fig. 18, and the gradient in the rough tube was found to be greater than that in the smoother tube by 22 per cent. When reduced, however, to the same linear speed through the tubes (by means of the ratio of the "free areas" of the cores and the assumption that the pressure gradient varies as the 1.7 power of the speed) the difference becomes 12 per cent.[17]

[17] While for some types of core there is considerable variation between individual air tubes, these types show very good uniformity, and this figure is probably good for the core as a whole.

34. Effect of Heat in the Radiator.—The surface friction in the air tubes also depends upon the temperature difference between the air and the radiator. The pressure gradient in the type C–9 was measured both when the radiator was cold and when heat was supplied, as in calorimetric tests, and the gradient was found to be about 15 per cent higher when hot than for the same air flow when cold, with a mean temperature difference of 61° C (110° F) between the water in the radiator and the entering air. This comparison is shown for three speeds in Fig. 19.

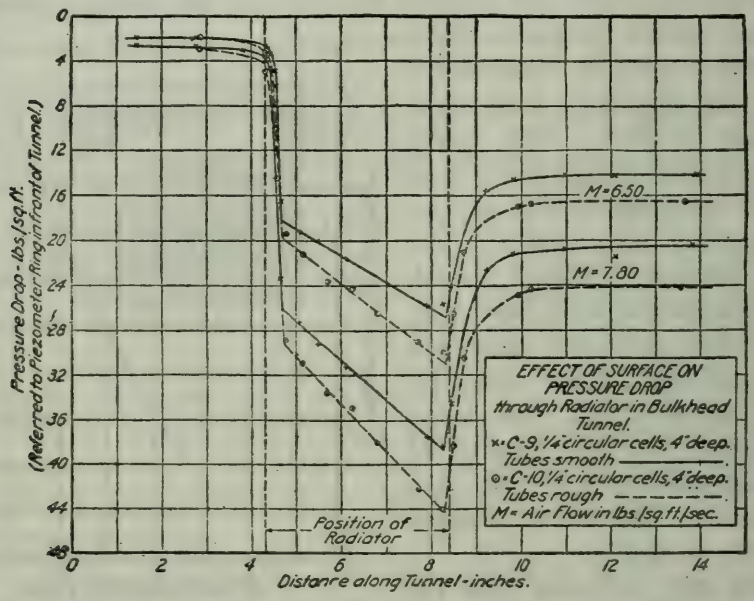


Fig. 18.—*Effect of roughness of surface of the air tube of a radiator on surface friction*

Two radiator cores similar in other respects show a difference of 12 per cent in the pressure gradients for the same air flow

The statement has been made by other investigators that increase in head resistance due to temperature difference can be computed from the increase in momentum of the air as it is heated, and consequently made less dense; and it may be well to point out that while such reasoning may apply to pressure gradient for a given rate of mass flow through the radiator, there is some question about its applicability to head resistance at a given flying speed. The expansion of the air on being heated in the radiator tube tends to do two things, picturing the air stream moving and radiator stationary—to push the air out from the rear face at a higher velocity than it had at entrance, and to develop a back pressure, acting against the pressure that drives it through the tube.

This back pressure tends to retard and reduce the air flow, and by so doing to decrease the surface friction and consequently the head resistance. On the other hand, a decrease in air flow through the radiator requires that a greater part of the approaching air shall be deflected around it, and this condition tends to increase the head resistance. Until more experimental evidence is available the question of the effect of temperature difference on head resistance must be left open, although no doubt exists as to the effect on that portion of head resistance comprised in the surface friction.

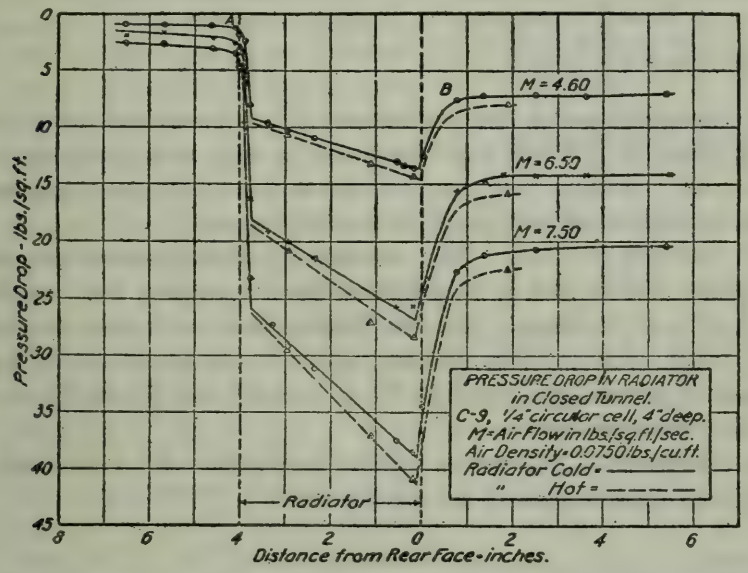


FIG. 19.—*Effect of heating the metal in the walls of a radiator air tube on surface friction*

For a given rate of air flow the same radiator tube was found to offer 15 per cent more surface friction when heated 61° C (110° F); the pressure gradient is 15 per cent larger

C. HEAD RESISTANCE OF THE CORE

35. FLYING SPEED AND AIR DENSITY.—Head resistance of the core, including both surface friction in the tubes and "eddy resistance," is proportional to the density of the air and nearly to the square of the flying speed and over a considerable range of size is also proportional to frontal area. The relation to density is in general use by aeronautical engineers, and although an indirect verification was obtained by measurements of pressure drop made in the reduced pressure tunnel, it seems unnecessary to include a proof in this discussion. The variation with speed was determined for 30 sections of radiator core, and the powers of the speed to which the head resistances were proportional are shown in Table 8.

TABLE 8.—Variation of Head Resistance of Core With Flying Speed

Radiator No.	Power of speed	Radiator No.	Power of speed	Radiator No.	Power of speed
A-7	1.96	A-30	1.95	C-16	1.97
A-8	1.94	A-31	1.93	D-1	1.94
A-13	1.96	A-32	1.90	D-2	1.98
A-15	1.94	B-18	2.00	D-3	1.98
A-23	1.98	B-19	1.95	D-4	1.93
A-25	2.05	B-20	1.99	E-4	2.02
A-26	1.98	B-21	1.98	F-6	2.03
A-27	1.96	C-2	1.96	G-1	1.99
A-28	1.94	C-2a	1.95	G-3	1.88
A-29	1.90	C-15	1.96	G-4	1.84

Mean of above 30 values, 1.954.

In many instances head resistance of core sections other than those listed in Table 8 was measured at only one speed, or over only a very narrow range, and in those cases the mean exponent 1.954 was used for extrapolation to other speeds.

36. Effect of Size.—The relation to frontal area has been discussed above, and it is sufficient here to repeat that no variation of head resistance per unit frontal area with size or shape was found with sections ranging from 20 cm by 20 cm (8 by 8 inches) to 40 cm by 40 cm (16 by 16 inches) and 30 cm by 60 cm (12 by 24 inches).

37. Empirical Equation.—Head resistance of a core may be computed approximately by the equation

$$R = c_1 \rho S^2$$

where

R = head resistance, force per unit frontal area,
ρ = air density,
S = flying speed,
c_1 = a constant for each type of core.

If R is expressed in pounds per square foot, ρ in pounds per cubic foot, and S in miles per hour, c_1 ranges for cellular radiators with straight-sided air passages, from 0.013 for cores with very great free area to 0.031 for cores with very small free area; for fin-and-tube types, unless very open, it exceeds 0.027; and for irregular types with turbulence vanes it may run as high as 0.035. If R is expressed in kg/m^2, ρ in kg/m^3, and S in m per sec, the corresponding values of c_1 are, respectively, 0.020, 0.047, 0.041, and 0.054.

38. Effects of Design of Core.—The factor c_1 is a function of the form and dimensions of the core and of the condition of the cooling surfaces, but the form of the function has not been determined. The features of design that cause air flow to be low are almost, if not quite, identical with those which cause high head resistance. Head resistance increases with decrease of free area and with increase of depth, although the increase with depth is not rapid. The eddy resistances at the front and rear faces are so great that if the sides of the air passages are straight and fairly smooth an increase of an inch or two in their length does not increase the total resistance very greatly. The effect of smoothness of tube surface on head resistance is evidently in the same direction as the effect on surface friction in the tubes, but less pronounced because the surface friction constitutes only a part of the resistance. Polishing the surfaces may reduce the resistance slightly, but no very marked effect will be produced without a considerable change in the character of the surface. Head resistance of a core of the type C–8, with headers (water boxes, top and bottom), was measured both before and after the tubes had been smoothed. The difference in resistance is shown in Fig. 20. The core of the section used was 20 cm (8 inches) square, and at 27 m per sec (60 miles per hour) the difference in resistance is seen by the plot to be about 0.24 pound. The resistance of an 8-inch section without headers is, from Table 21, 2.53 pounds at this speed, or the change in resistance due to smoothing the tubes was nearly 10 per cent. This difference is greater than would ordinarily be obtained by polishing the tubes of a radiator because the surface was unusually rough. Head resistance is increased considerably by projections, indentations, holes, or discontinuities of any kind in the walls of the air passages, since they introduce eddy resistance into the passages themselves. The types B–19 and B–20 illustrate the effect of holes in the tube

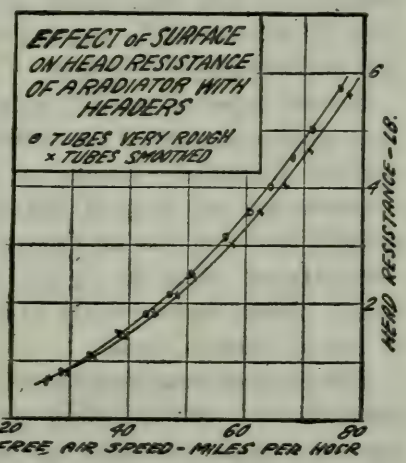


Fig. 20.—*Effect of roughness of surface of air tubes of a radiator on head resistance of the radiator*

With unusual extremes of roughness a difference of 7 per cent of the resistance of the radiator, or 10 per cent of the resistance of the core, was found

walls, the head resistance constant of the perforated type B–19 being 13 per cent greater than that of the unperforated type, although the latter is one-half inch deeper. Except in perforations and in depth the types are similar, the dimensions and form matching B–1 (Fig. 71). Fin-and-tube types show particularly high head resistance, often partly because of their small free area, but even in the more open types the eddy resistances set up at each water tube make the total resistance very high. Spiral vanes, or other devices for increasing turbulence of the air, increase the head resistance greatly, and in every case where a reliable comparison has been made the increase has been found greater than is warranted by the increase in heat dissipation except for use in obstructed positions.

Certain types of core E–1 to 5, E–9, and E–10 are so constructed that short columns of air vibrate *across* the direction of air flow, and by alternately forcing air into the fast moving stream and withdrawing air from it act as a very effective drag upon it, greatly reducing the air flow and increasing the head resistance. These types when in an air stream produce a shrill whistling sound, which varies widely in intensity and in pitch as the speed of the air stream varies.

The plots of head resistance against flying speed show irregular curvature for the whistling types, and in taking observations it was very noticeable that the irregularities occurred at speeds at which the tone of the whistle changed suddenly.

39. YAW.—The effect of yawing the radiator, or turning it so that the air strikes it at some other angle than normal to its face, is, in general, to increase the resistance for angles of yaw (angle between direction of the stream and the normal to the face) up to at least 30 or 40°. Fig. 21 shows typical curves of resistance in terms of angle of yaw. The types A–13 and C–15 are representative of ordinary cellular radiators, while the others are unusual types of core.

D. HEAD RESISTANCE CHARGEABLE TO THE RADIATOR

Head resistance chargeable to the radiator includes surface friction, eddy resistance at the radiator, and every effect of the radiator and aircraft upon each other that makes the total resistance of the craft greater than it would need to be if it could be designed without a radiator.

40. UNOBSTRUCTED POSITIONS.—For unobstructed positions the head resistance of the core may be regarded as equal to the head

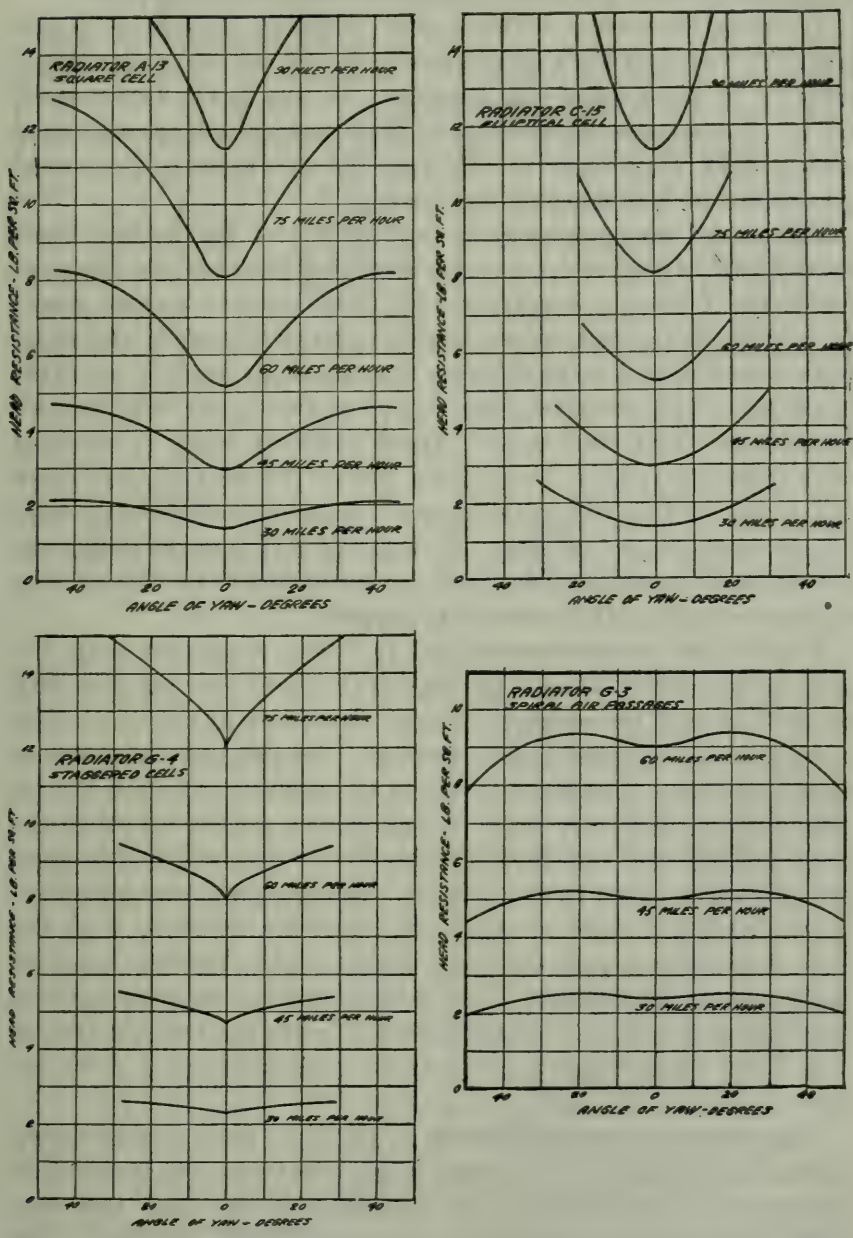


FIG. 21.—*Effect of yaw on head resistance of a section of radiator core*

Upper charts are for cells of common types, lower ones for unusual types of core

resistance chargeable to the radiator, except for the comparatively small resistance of the tanks or headers and connecting pipes.

41. Nose Position.—The model fuselage described above (art. 23) was used for a qualitative study of the effect of using a radiator in the nose of the fuselage. It was not a true model, for no attempt was made to build it to scale, but it showed very clearly that a radiator in the nose of the fuselage adds very greatly to the resistance of the fuselage.

The model was mounted on the balance of the 54-inch wind tunnel, and its head resistance was measured like that of a radiator, under the following conditions: (1) Nose crudely stream lined; (2) stream-line nose removed and a radiator placed in the nose, but covered with a sheet of paper to exclude air flow; (3) radiator in the nose, with air flowing through it, and with side vents closed, partly open, and wide open. Three different types of radiator were used—B–1, very open; A–23, one of the best of the square cell types; and G–3, a very compact type characterized by high heat transfer at low air flow. No attempt was made to design the best possible nose, and the form used was made by intersecting cylindrical surfaces but served its purpose.

The results are shown in Fig. 22. The resistance with the stream-line nose was about one-half of that with the flat nose with no air flow, and the resistance increased rapidly as the vents were opened and air allowed to flow through. Reasons for this increase are easily seen. The air that enters the radiator does not have a clear, straight path out of the fuselage, but is greatly retarded and must find its way out through the sides,[18] after which it is again brought up to speed by the stream. Furthermore, any air escaping through the sides of the body interferes seriously with the flow of the stream past the body, which might otherwise conform fairly well to stream lines. The addition of louvres over the side openings to direct the air backward as it came out into the stream was found to decrease the resistance somewhat for a given air flow.

The effect of the nose radiator is, perhaps, most clearly shown in Fig. 23, in which a comparison is made between the installation in the nose of the fuselage and a radiator of the same type and equivalent cooling capacity in an unobstructed position. The curves are computed for each of the three radiators used, and for flying speeds of 60 and 90 miles per hour (27 and 40 m per second),

[18] This statement applies to the wind tunnel. In actual flight the air is picked up by the fuselage as by a scoop and acquires a speed approaching that of the plane before making its escape.

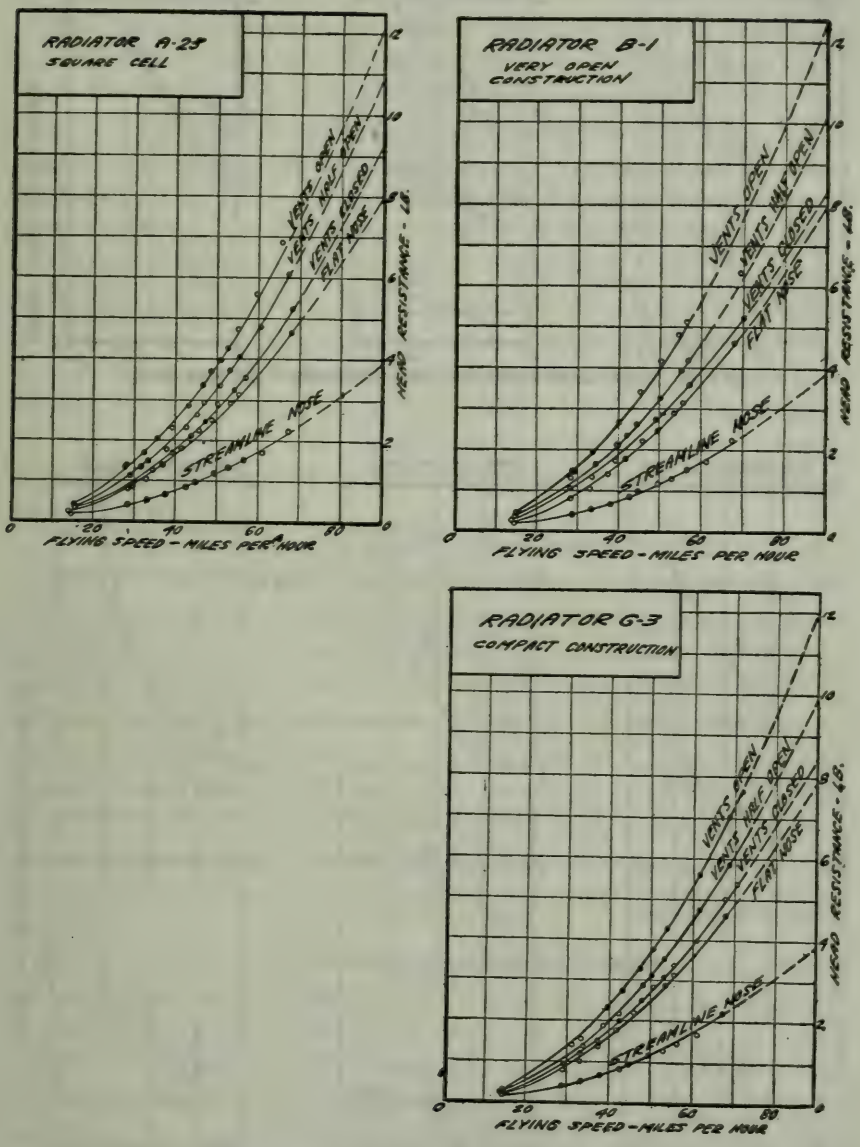


FIG. 22.—*Head resistance of model fuselage with nose radiators*

The differences in total head resistance are not large, notwithstanding great differences in cell structure and in heat transfer properties of the several radiator cores illustrated. Note great increase in total head resistance of fuselage with any nose radiator over the value with a stream-line nose

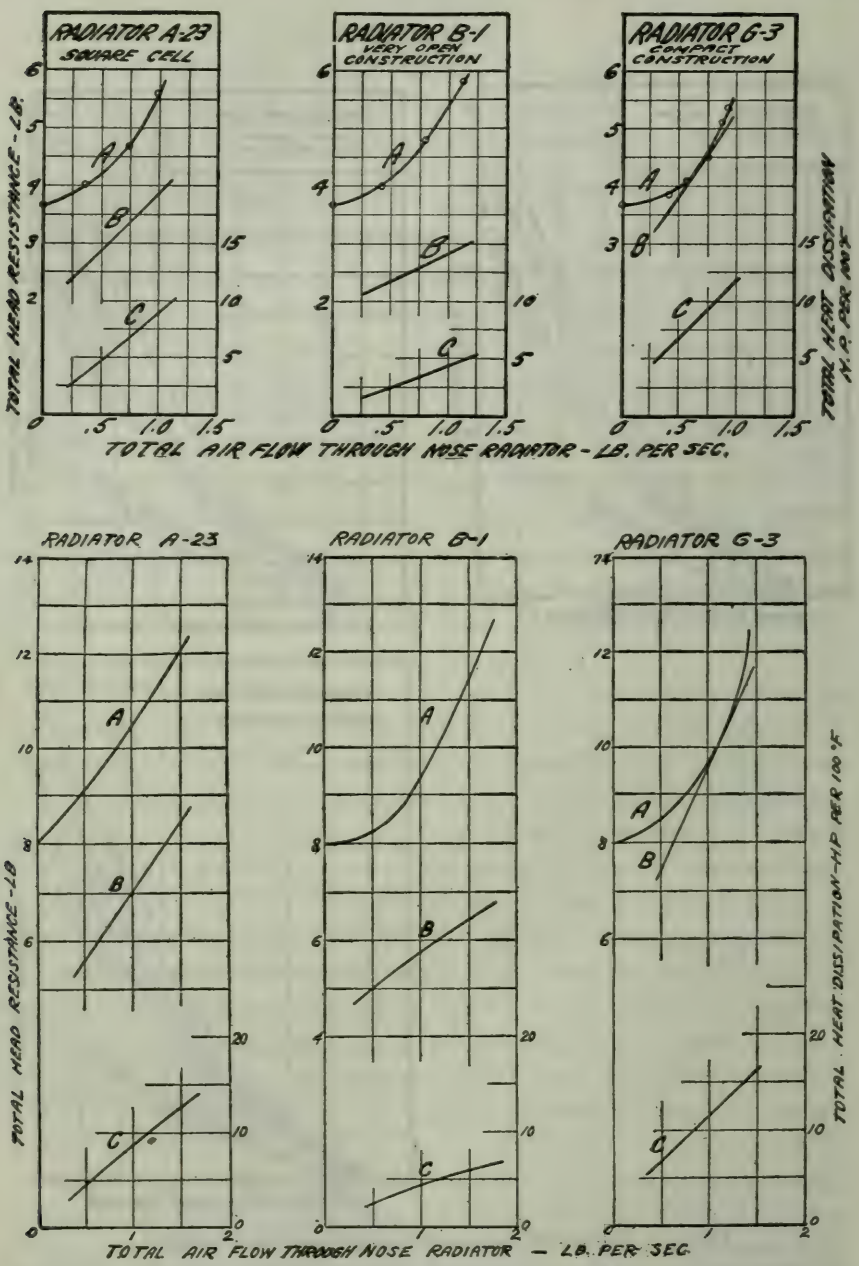


FIG. 23.—*Comparative value of the head resistance offered by a fuselage with radiator mounted in nose, and same fuselage, stream lined, plus a radiator of equal cooling effectiveness and similar construction, mounted in unobstructed position*

The latter arrangement is shown to be decidedly superior for the three types of core tested at the wind speeds of 60 and 90 miles per hour (26.8 and 40.2 meters per second). Symbols A, B, C, explained on p. 299.

showing resistances in terms of the amount of air flowing through the nose radiator. Curve *A* is in each case the resistance of the model fuselage with its nose radiator, while curve *B* shows on the same scale the sum of the resistance of the fuselage when fitted with the stream-line nose and the resistance of a section of the same kind of core in an unobstructed position of such size as to give the same rate of heat dissipation. Lest the curves might seem to indicate that the three types of radiator are about equally good in the nose position, but greatly different in unobstructed positions, a third curve *C* is added, showing heat dissipation for each type in terms of air flow through the core, and a comparison of heat dissipation shows that a much larger radiator of the type B–1 would be needed to cool a given engine than of the type G–3. In fact, if such a type as B–1 were used in the nose of the fuselage to cool an engine of fairly high power, so large a radiator would probably be required as to necessitate enlargement of the fuselage to contain it.

The curves should not be interpreted to mean that the type G–3 is good for the nose position, but rather that if a radiator is to be taken from an unobstructed position and placed in the nose of the fuselage this type would show less ill effect than the others. It has very high head resistance in unobstructed positions. If, in spite of the great increase in head resistance of the assembly, the designer insists upon mounting the radiator in a nose position he should choose a type that will give maximum heat transfer with very low air flow, even at the expense of high head resistance of the core, since any considerable air flow through the core will increase to a marked degree the head resistance chargeable to the radiator.

42. Wing Positions.—A limited study of the effect of a radiator on the properties of a wing was made by the use of the half-size section of wing described above (art. 24). Both the "lift" and "drift" of the wing section were measured before the fabric had been cut away for the radiator and after the radiator had been inserted. The measurements were made in the 54-inch wind tunnel on the balance described above (art. 27), which was suspended on an arm of a second balance, so that vertical forces ("lift") could be measured as well as "drift." With the object of determining approximately the center of pressure on the wing, the balance arm supporting it was extended to two different positions. The computations involved taking the differences between quan-

tities so nearly equal that the differences were but little greater than the limits of experimental error. The results were naturally very erratic, requiring considerable fairing to give smooth curves, and must be regarded as only qualitative, since errors of 8 per cent in lift and 25 per cent in drift are quite probable. Four angles of incidence were used, and Fig. 24 shows that the radiator may cause a decrease in drift at certain positions and an increase at others, while it decreases the lift at all angles.

43. Slip-Stream Positions.—If the radiator is in the propeller slip stream, the head resistance chargeable to it is probably approximately equal to what it would be if the propeller could be removed and the craft driven by other means at such a speed as would give the same speed of air past the radiator. If this is true, an assumption that the slip-stream speed is, for example, 20 per cent greater than the speed of flight would mean an increase of 44 per cent in head resistance over the value corresponding to the flying speed, since the resistance varies as the square of the speed. A slight further increase is caused by the swirl of the slip stream, which is similar to the effect of yawing the radiator. On the other hand, the effect of slip stream for positions such as the nose of the fuselage, which would be obstructed without the propeller, is that the virtual yaw of the slip stream tends to decrease the air flow through the core and may to a small extent compensate for the increased slip-stream speed by reducing the head resistance chargeable to the radiator, since for such positions high air flow is accompanied by high head resistance.

E. POWER ABSORBED

As stated above, the power absorbed by a radiator may be divided into two parts, due to head resistance and to weight; and, as in the case of head resistance, the power absorbed by the core is only a part of that chargeable to the radiator.[19]

44. Power Absorbed by the Core.—The power absorbed in overcoming the head resistance of the core is equal to the product of the head resistance by the flying speed and by a conversion factor depending upon the units used, and since the head resistance is approximately proportional to the square of the speed this fraction of the power absorbed is approximately proportional to the cube of the speed. The weight is supported by a vertical component of the air pressure on the wing, called the "lift,"

[19] Since in this report power absorbed is reduced to unit frontal area, the statements apply to power absorbed by a particular radiator rather than to the power absorbed in cooling a given engine.

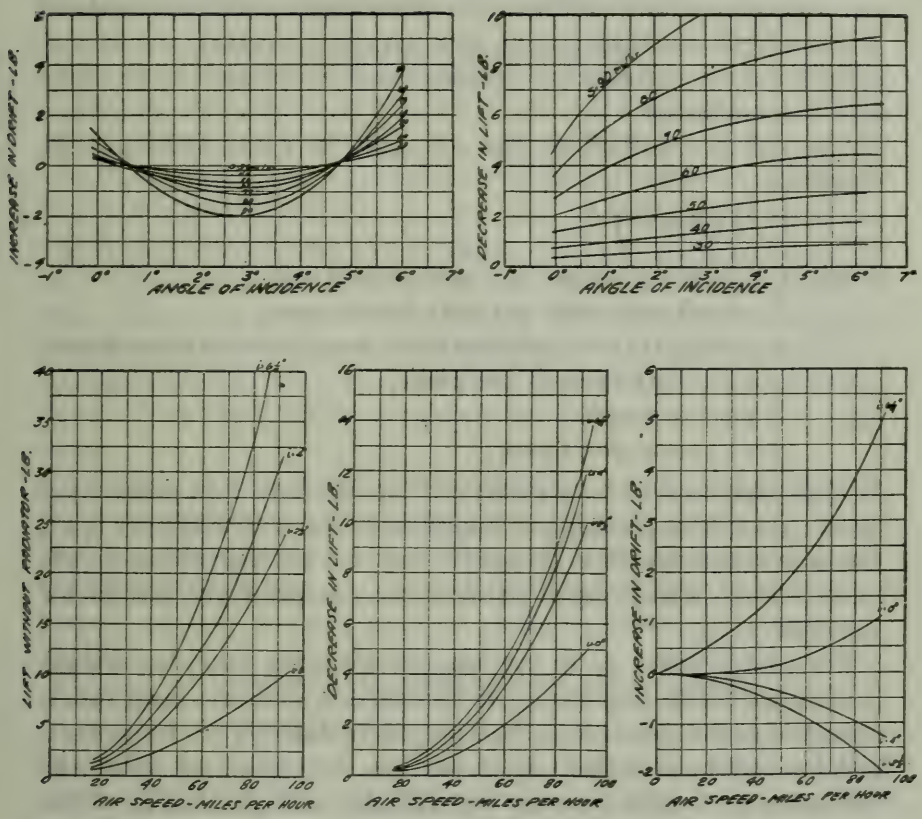


FIG. 24.—*Effect of a radiator in wing section upon the aerodynamic forces acting on the wing*

Upper curves show that for all speeds there is a decrease in lift, regardless of angle of incidence, i, but that drift may be either increased or decreased by the presence of the radiator, depending on angle of incidence. Lower curves show same data plotted with air speed, s, as abscissas. (A radiator is a partial "hole" in the wing, permitting restricted passage of air, thus breaking down the pressure difference which it is the function of the wing to preserve, and from which the lifting force on the plane is obtained)

which is accompanied by a corresponding horizontal component, or "drift." The ratio of "lift" to "drift" varies for different types of wing and for different angles of attack, but if it is known for the particular craft on which a radiator is mounted the weight may be reduced to an equivalent head resistance by dividing by this ratio of lift to drift. In this report a lift-drift ratio of 5.4 has been assumed as one that represents rather severe conditions for the radiator and assigns equal importance to climbing and to level flight.

The power absorbed by the core may be computed from the equation

$$P = c\left(R + \frac{w}{r}\right) S$$

where P = power absorbed per unit frontal area,
R = head resistance per unit frontal area,
w = weight of core and contained water per unit frontal area,
r = lift-drift ratio of the plane,
S = flying speed,
c = a conversion factor.

If P is expressed in horsepower per square foot, R in pounds per square foot, w in pounds per square foot, and S in miles per hour, the conversion factor is 0.00267. For the corresponding metric units kw/m², kg/m², kg/m², and m/sec., respectively, the factor is 0.0098.

For speeds below 30 m per sec. (60 miles per hour) the weight is of considerable importance in comparison with the head resistance, but as the speed increases it becomes relatively less important, and for speeds as high as 45 m per sec. (100 miles per hour) the difference in weight between one radiator and another is of but small importance.

45. Power Absorbed Chargeable to the Radiator.—Equation (1) (art. 44), for power absorbed by the core, is also applicable to power absorbed chargeable to the radiator, if head resistance chargeable to the radiator is substituted for head resistance of the core, but the equation is of limited use because of the difficulty of obtaining the value of head resistance chargeable to the radiator. This equation ignores the power used in driving the water pump, which is usually a very small part of the engine power, and has been omitted from this discussion.

Power absorbed chargeable to the radiator is evidently high for such installations as cause high head resistance chargeable to the radiator, notably the position in the nose of the fuselage

and slip-stream positions. Since the part of the power absorbed that is due to head resistance alone (neglecting weight) is proportional to the cube of the speed, an assumption of 20 per cent increased air speed in the slip-stream represents an increase of 73 per cent in that part of the power absorbed, while the increase in the part due to weight is only 20 per cent.

IV. HEAT DISSIPATION

The transfer of heat from water to air takes place in three stages—from water to metal, through the metal, and from metal to air. In each stage the transfer is proportional to the appropriate temperature difference, and in the first and third it depends upon the speed and turbulence of flow. The heat transfer is not proportional to the amount of cooling surface provided in the radiator for two reasons: The air is warmed and the water cooled appreciably in passing through the radiator, so that the temperature difference between them is less at the rear face than at the front, and indirect cooling surface is less effective than direct.

It seems reasonable to assume that the transfer of heat from water through the metal to the air is proportional to the difference in temperature between the water and the air, and as an experimental verification of the assumption was found in a French report[20] it was adopted without further experimental study.

A. EXPERIMENTAL METHOD AND COMPUTATION

46. Wind Tunnels.—The "steam" tunnel partially described in article 7 (Figs. 2, 3) as first built was equipped for using superheated steam as a source of heat, hence its name. As rebuilt later, hot water was used for calorimetric measurements in place of steam, and parts of the equipment were borrowed from the "reduced pressure" wind tunnel. The wind tunnel equipment will accordingly be described under three subtitles—steam tunnel using steam, reduced pressure tunnel (using water), and steam tunnel using water.

(a) STEAM TUNNEL USING STEAM

47. Apparatus.—In the steam tunnel as first built air was pushed through the channel by a 36-inch (91 cm) Sturtevant blower driven by a 220-volt direct-current shunt motor rated at 10 h. p. (7.5 kw). By the use of rheostats in both field and arma-

[20] Bulletin de la Section Technique de l'Aeronautique Militaire, August, 1918, p. 27.

ture circuits and by throttling the intake of the fan air speeds from 4.5 to 45 m per sec. (10 to 100 miles per hour) could be obtained in the working section, which was square, 20.3 cm (8 inches) inside measurement. The tunnel was built in two sections to allow insertion of the radiator, the outlet section being supported by a frame on casters. The parts adjacent to the radiator were inlaid with sheet brass and equipped with pitot grid and piezometer rings connected to pressure gages, as described above (art. 7), and indicated in Fig. 3. Extra boards on the sides and bottom of the tunnel facilitated alignment of the two sections and the radiator.

The steam connections are shown in Fig. 25. Steam from the high-pressure mains was passed through a controlling valve, where its pressure was reduced to about 0.7 kg/cm² (10 pounds per square inch); a U-shaped pipe at the bottom of which a valve partly open allowed most of the water to drain out; a coil, where it was heated to from 110 to 150° C (230 to 300° F); a plug cock, where its pressure fell to approximately atmospheric; a separator, where its temperature was measured with a mercury thermometer; the radiator, where most of it was condensed; and another separator from which the condensed water dropped into a weighing tank.

In preliminary work a thermometer was inserted in the lower header of the radiator, but the water temperature was found to vary so slightly from the temperature of condensation that the heat involved in the cooling of the water in the radiator could be neglected. Magnesia pipe covering was used to reduce heat losses from the steam pipes, and the sides of the radiator were lagged with cork board 1.3 cm (½ inch) thick. The headers were sometimes covered with hair felt, but their surface was so small and the air flow past them so low that errors due to loss of heat from the headers were neglected.

48. Observations.—The drain valves in the steam line were opened, the water drained off, and the blower for the air stream in the wind tunnel started. When the water was out of the line and the steam flowing well, the gas heater was lighted, the blower adjusted to give the desired speed, and the valves and the heater adjusted so that steam showed faintly at the lower separator. After steady conditions of temperature and steam flow had been attained one observer set the balance slightly ahead of the actual weight and started a stop watch when the pointer of the balance crossed the zero line. Then weights of from 1 to 10 pounds, depending upon the probable rate of condensation, were added to

the balance. One observer recorded steam temperatures and adjusted the valves when necessary to maintain steady flow, while the other observer read the differential pressure gages and the temperature of the air at entrance to the radiator. About a minute before the assigned weight of steam was condensed a bell warned the observers, who prepared to note the time at which the pointer of the balance again crossed the zero line. The time

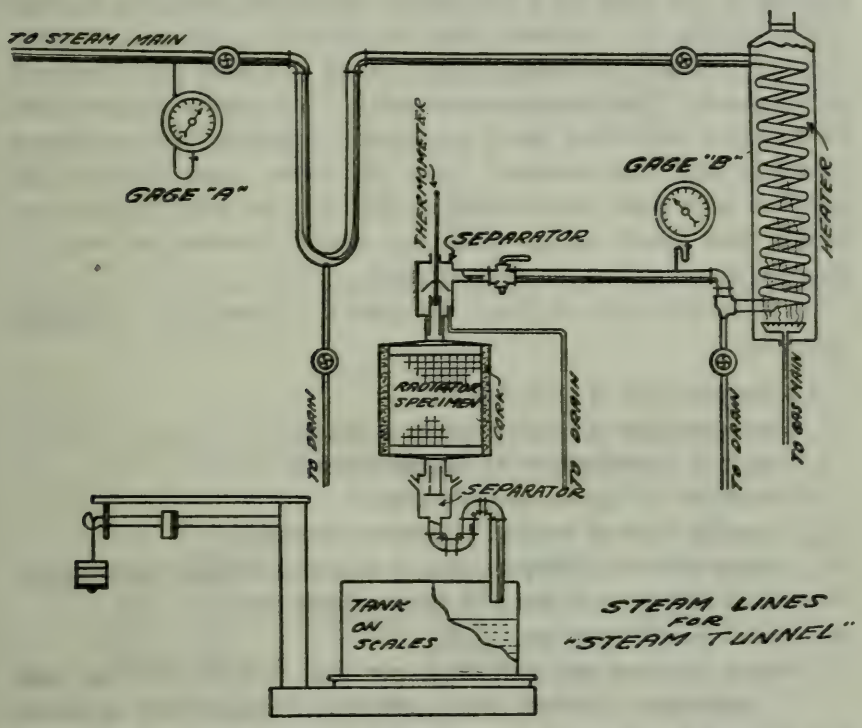


FIG. 25.—*Diagram of steam connections for calorimetric measurement of radiators in small wind tunnel*

The heat delivered to the air stream per unit time was measured by weighing steam condensed in the radiator water tubes

interval varied between three and six minutes and could easily be measured to one second. The balance readings were within 0.01 pound (5 g). At each air speed two or three runs were made for a check.

The observed quantities included (1) differential pressure between the pitot grid and its piezometer ring, (2) differential pressure between piezometer rings before and behind the radiator, (3) temperature of the air in front of the radiator (read on a mercury thermometer), (4) temperature of steam at entrance to radi-

ator, (5) weight of steam condensed, (6) time of condensation, (7) barometric pressure in the room, (8) relative humidity, (9) differential pressure between the channel in front of the radiator and outside air.

49. COMPUTATION OF AIR FLOW.—Air flow was computed as explained in article 10. Pressure drop in the air stream in passing through the radiator was computed by multiplying the reading of the gage by a conversion factor and applying a small correction for the pressure drop in 36 cm (14 inches) of unobstructed channel, determined by a blank run with no radiator in the channel. This measurement, originally intended to give some information regarding head resistance, appeared to be almost valueless and was omitted from the later tests, because the pressure drop when the radiator section fills the wind tunnel completely was found not to bear any simple relation to head resistance measured in the open tunnel.

50. COMPUTATION OF HEAT TRANSFER.—Using any consistent units, let

θ = temperature of entering air,
T_c = temperature of condensation of steam,
L = heat of vaporization at temperature T_c,
s = number of degrees of superheat,
C_p = specific heat of steam at constant pressure,
T_m = mean effective temperature of steam and water in radiator,
H_s = heat lost by unit mass of steam condensed,
H_1 = heat transfer per unit time,
H_2 = heat transfer per unit time per unit frontal area per unit difference between mean effective temperature of steam and water and temperature of entering air,
w = weight of steam condensed,
τ = time of condensation,
c, c' = conversion factors, depending upon units used.

Now
$$H_s = L + C_p s. \tag{1}$$

In computing the mean effective temperature of the steam and water the temperatures were weighted according to the amount of heat lost at each temperature, so that T_m was defined as

$$T_m = \frac{\left(T_c + \frac{s}{2}\right) C_p s + T_c L}{C_p s + L}. \tag{2}$$

With the aid of equation (1) this may be reduced to

$$T_m = T_c + \frac{C_p}{2H_s} s^2.$$

The term $\frac{C_p}{2H_s}$ represents a small correction and is a function of the superheat s, since the range of condensation temperatures is so small that the heat of vaporization may be regarded as constant. For convenience in computation Table 9 of values of this correction for different values of s was computed from steam-table data. Similarly, the heat lost H_s was tabulated from different amounts of superheat. The rate of transfer of heat from the steam or water to the air, in units of power, is

$$H_1 = c\frac{H_s w}{\tau} \tag{4}$$

and the rate of transfer per unit time per unit temperature difference is

$$H_2 = c'\frac{H_s w}{\tau (T_m - \theta)}. \tag{5}$$

TABLE 9.—Properties of Superheated Steam Required for Computing Results of Radiator Tests Using Steam as a Source of Heat

[Pressure=15 lbs./in.²]

Superheat above temperature of condensation	Effective temperature correction above temperature of condensation	Heat per unit mass of steam condensed		Superheat above temperature of condensation	Effective temperature correction above temperature of condensation	Heat per unit mass of steam condensed	
			hp. sec.				hp. sec.
°C	°C	g cal/g	lb.	°F	°F	Btu/lb.	lb.
5	0.01	541.2	1377	10	0.02	974.7	1378
10	.04	543.6	1383	20	.10	979.4	1385
15	.10	545.9	1389	30	.22	984.1	1391
20	.17	584.3	1395	40	.38	988.8	1398
25	.27	550.6	1401	50	.59	993.5	1405
30	.38	553.0	1407	60	.85	998.2	1411
35	.52	555.3	1413	70	1.15	1002.9	1418
40	.67	557.7	1419	80	1.49	1007.6	1424
45	.85	560.0	1425	90	1.88	1012.2	1431
50	1.05	562.4	1431	100	2.31	1016.9	1438
60	1.49	567.1	1443	125	3.56	1028.5	1454
70	2.02	571.8	1455	150	5.07	1040.3	1471
80	2.61	576.5	1467	175	6.81	1051.9	1487
				200	8.82	1063.7	1504

The temperature difference $(T_m - \theta)$ was chosen instead of a difference between mean steam and water temperature and mean air temperature merely for convenience. The justification of this choice is given in Appendix E.

(*b*) REDUCED PRESSURE TUNNEL

51. APPARATUS—AIR SYSTEM.—The construction of the reduced pressure wind tunnel is shown diagrammatically in Fig. 6. Both the tunnel and the fan used for drawing air through it were inclosed in a steel tank about 1.5 m (5 feet) long and 90 cm (3 feet) in diameter, sufficiently tight to allow maintaining pressures as low as 30 to 40 cm (12 to 16 inches) of mercury. The fan was driven by a direct-current shunt motor rated at 5.5 kw (7.5 horsepower), which could be run on either 110 or 220 volts, and for further speed control was provided with rheostats in both field and armature circuits. A 38 cm (15 inch) Sirocco fan was used.

At the entrance to the tunnel a honeycomb of sheet-metal cells 2.5 cm (1 inch) square and 7.5 cm (3 inches) deep served to break up vortices and straighten the air flow. Following this in order came: (1) Pitot grid and piezometer ring for measuring air speed, (2) electric resistance thermometer for measuring air temperature, (3) thermocouple grid containing one set of junctions for measuring the rise in temperature of the air in passing through the radiator, (4) piezometer ring for measuring the drop in pressure in the air stream in passing through the radiator, (5) the radiator section, (6) third piezometer ring, (7) thermocouple grid containing the second set of junctions for measuring rise in air temperature, (8) fan, (9) conical guide vanes to deflect the air around the end of the tunnel and back around the outside of it, (10) wet-and-dry bulb hygrometer (in the return air stream), (11) cold-water radiator for cooling to original temperature the heated air during its return to the entrance of the tunnel.

The electric resistance thermometer for the measurement of air temperature at entrance to the radiator is described above (art. 11) and shown in Fig. 7. The thermocouple grids for the calorimetric measurement of rise in air temperature contained 25 copper constantan couples, with junctions equally spaced over the channel. An attempt was made to measure the rise in air temperature by the use of 200-ohm resistance thermometers of fine insulated nickel wire strung over a frame of iron wire, but the varying strains in the fine wire caused by the air stream resulted in such changes in resistance as to introduce large errors.

The thermocouples were calibrated, and the calibration expressed in the form

$$E = a\theta + b\theta^2$$

or

$$\frac{dE}{d\theta} = a + 2b\theta$$

where E = electromotive force of the couples, with cold junction at 0° C.

θ = temperature in degrees centigrade.

a, b, = constants.

This form of calibration was used throughout the work on radiators, the constants being determined for each spool of wire used.

52. Apparatus—Water System.—The source of heat for calorimetric measurements in the reduced pressure wind tunnel was hot

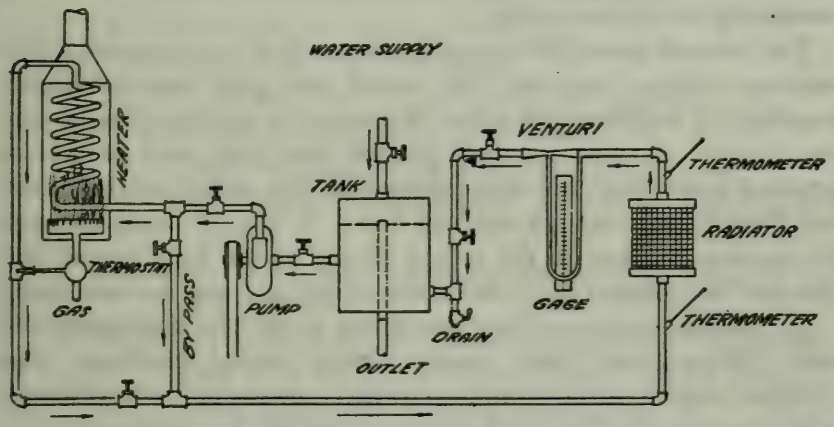


Fig. 26.—*Diagram of water system for calorimetric measurements of radiators in both the reduced pressure wind tunnel and the "steam tunnel" as rebuilt, superseding steam by hot water as the source of heat*

water. The flow of water was produced by a centrifugal pump driven by a direct-current shunt motor running on 220 volts and rated at 750 w (1 horsepower). A diagram of the piping system is shown in Fig. 26. The resistance of the coil of the gas heater was large in comparison with that of the remainder of the line, and a by-pass was provided for obtaining the higher rates of flow. A thermostat in the heater served to maintain approximately constant water temperature at the entrance to the radiator. After the heater, there followed in order: (1) Mercury thermometer in the water line used when necessary to adjust the thermostat, (2) one set of thermoelectric junctions for measuring drop in temperature of the water in passing through the radiator, (3) radiator

section, (4) second set of junctions of the thermocouples, (5) venturi meter for measuring the rate of water flow, (6) surge tank.

For the measurement of the drop in temperature of the water 21 thermocouples, with the similar junctions about 1.3 cm (½ inch) apart, incased in a copper tube in the form of a spiral coil, were placed in the pipes at inlet and outlet of the radiator. Previous work showed that thermocouples in the center of the water boxes did not give a satisfactory average temperature. In addition to the use of these thermocouples differentially to measure accurately the fall of temperature of the water, a connection to a reference junction in an oil bath whose temperature was measured to 0.1° C by a calibrated mercury thermometer measured approximately the temperature of the water. Thermal electromotive forces were measured on a potentiometer with accessories such as to give a sensitivity of 10 microvolts.

The venturi meter for measuring water flow was connected to a mercury U-tube gage and the meter and gage were calibrated together by weighing the water discharged in a given time at constant rates. A 3 m (10 foot) gravity head was used at first to produce water flow, but was replaced by the pump because it did not furnish high enough rates of flow. A flow of water through the cooling radiator in the return circuit of the wind tunnel was obtained by connecting to the water mains and was not measured.

53. Observations.—Care was taken to let the machinery run until temperatures were steady before taking readings. One observer read the electrical instruments measuring temperatures, while another observer read the gages and the hygrometer.

The quantities observed included the following: (1) Differential pressure between the pitot grid and its piezometer ring, (2) differential pressure between piezometer rings before and behind the radiator, (3) temperatures of wet and dry bulb hygrometer, (4) barometer pressure at the piezometer ring corresponding to the pitot grid, (5) temperature of the barometer, (6) differential, pressure of the venturi gage, (7) temperature of the venturi gage (8) resistance of the resistance thermometer, (9) e. m. f. of thermocouples for rise in air temperature, (10) e. m. f. of thermocouples for drop in water temperature, (11) e. m. f. of reference couple for water temperature, (12) temperature of the oil bath.

The complete calorimetric test of a section included the following sets of runs: (1) Atmospheric pressure, constant water flow, varying air flows; (2) constant air flow (mass flow), constant

water flow, varying pressures, and air speeds; (3) constant pressure, constant air flow, varying water flow.

54. COMPUTATION.—*Air flow* was computed as explained in art. 10. *Water flow* was obtained directly from the readings of the venturi meter and a conversion factor depending upon the calibration constants and the units used. *Heat dissipation* was computed by two methods—heat received by the air and heat lost by the water— and the two measurements being independent furnished a good check on the observations. *Temperatures* were determined from the potentiometer readings for the thermocouples and their calibrations.

Using any consistent units, let

M = air flow in mass per unit time per unit frontal area,
C_p = specific heat of air at constant pressure,
W = water flow in mass per unit time,
θ = temperature of entering air,
θ_2 = temperature of air on leaving the radiator,
θ' = temperature of entering water,
θ'_2 = temperature of water on leaving the radiator,
θ'_m = mean water temperature (taken as arithmetical mean),
H_1 = heat dissipation (water to air) per unit time per unit frontal area,
H_2 = heat dissipation per unit time per unit frontal area per unit difference between mean water temperature and temperature of entering air,
c_1, c_2, c_3, c_4 = conversion factors, depending upon units used.

Heat received by the air is given in the two forms by the equations

$$H_1 = c_1 M C_p (\theta_2 - \theta)$$
$$H_2 = c_2 M C_p \frac{(\theta_2 - \theta)}{(\theta'_m - \theta)}.$$

Heat lost by the water is given by

$$H_1 = c_3 W (\theta_2' - \theta')$$
$$H_2 = c_4 W \frac{(\theta_2' - \theta')}{(\theta'_m - \theta)}.$$

The quantities which enter both expressions for H_2 are all given directly by the experimental data except c_2, c_4, C_p, which are readily ascertained, and the quantity θ'_m which comes indirectly from the observed data by very simple arithmetic.

(c) STEAM TUNNEL USING WATER

55. ADAPTATION TO USE OF WATER.—The rebuilt steam tunnel differed from the one first built (described in art. 47), mainly in using the blower to draw air through the channel instead of pushing it through and in being equipped for the use of hot water as a source of heat. Water circulation was obtained by piping to this tunnel the water system of the reduced-pressure tunnel (art. 52, Fig. 26). In the air system of the tunnel a bell mouth and a honeycomb at the intake were added to straighten the flow. Fig. 2 is a photograph of this wind tunnel as rebuilt, with the intake section moved back to show the mounting of the radiator.

Mercury thermometers in the tunnel before and behind the radiator and in the water line at inlet and outlet furnished a rough check on the measurement of heat dissipation. The temperature drop in the water was too small to be measured with accuracy by the thermometers, and the readings of the thermometer beyond the radiator were, in general, not reliable for anything better than a rough check. The governing computation of heat dissipation was accordingly made from the air flow and the rise in air temperature as indicated by the thermocouple grids, which were those used in the reduced-pressure tunnel (art. 51).

B. HEAT TRANSFER, WATER OR STEAM TO METAL

56. GOVERNING CONDITIONS.—The rate of transfer of heat from the circulating water to the metal walls of the water passages depends upon the temperature difference between water and metal, upon the rate of flow of water, and upon the degree of turbulence in the stream. The third factor depends upon the second, and the heat transfer per degree mean temperature difference is considerably less at very low rates of flow than at high rates. As the rate of flow is increased the corresponding increase in heat transfer per degree becomes less and less, and at the high rates of flow ordinarily used in aeronautic practice differences in the rate of flow have only neglible effects upon the transfer per degree.

Data showing in detail the effect of changes in rate of water flow are given in the curves of Appendix G (Figs. 128–137). The conclusion drawn from these data is that for all types of core commonly used any water flow exceeding 3 gallons per minute per inch depth of core (1 foot wide) gives substantially the same heat dissipating performance of the core. With a flow so small as 2 gallons per minute per inch depth of core the heat dissipation is, in general, not lowered seriously, but below this rate of water flow

the effect rapidly becomes more marked, as indicated by the curves to which reference is made. The numerical values relating to the conclusions stated above are exhibited in Table 10 for many types of core. The column headed "Maximum heat dissipation" was obtained by estimating the positions of asymptotes to the curves forming Figs. 128–137.

TABLE 10.—Relation of Heat Dissipation to Rate of Flow of Water

Radiator No.	Depth of core	Air flow per unit frontal area	Maximum heat dissipation	Water flow of 3 gallons per minute per inch depth of core		(Water flow of 2 gallons, etc.) Deficiency from maximum
				Heat dissipation	Deficiency from maximum	
		Lbs.	hp.	hp.		
	Inches	ft.²x sec.	ft.²x 100° F	ft.²x100° F	Per cent	Per cent
A-23	5	2.04	19.0	18.5	3	3
		2.95	26.5	25.9	2	4
		4.10	33.7	33.0	2	4
		4.45	35.8	35.3	2	2
B-3	3	2.63	12.7	12.2	4	5
		3.82	16.8	16.1	4	8
		5.12	20.4	19.8	3	7
		5.58	22.6	21.8	4	10
B-5	2	2.42	11.6	11.2	4	6
		3.54	14.8	13.9	6	10
		4.89	17.6	16.7	5	8
		5.33	18.6	17.6	6	8
B-8	5.3	1.94	18.0	17.4	3	8
		2.86	22.3	21.8	3	6
		3.98	28.8	28.0	3	7
B-9	3.5	2.10	14.5	14.2	2	5
		3.12	20.3	19.4	4	10
		4.30	25.2	24.4	3	6
		4.80	29.0	28.0	3	7
C-6	3	2.20	15.1	14.6	3	5
		3.38	20.7	20.2	3	4
		4.61	26.4	24.8	6	9
		5.07	28.2	26.7	6	10
D-1	2.7	2.26	13.8	13.0	6	9
		3.45	18.2	17.2	6	8
		4.52	22.0	20.6	6	10
		5.00	23.8	22.4	6	9
F-5	3.5	1.60	15.7	15.0	4	8
		2.30	19.3	18.2	6	8
		3.18	23.4	22.1	5	9
		3.54	24.5	23.0	6	9
G-2	1.7	2.06	15.8	14.5	8	16
		3.02	20.5	18.7	9	15
		4.15	23.7	22.5	5	12
		4.52	25.5	23.6	8	11
G-4	4	2.05	23.2	22.8	2	4
		3.44	33.2	32.6	2	4

Accordingly, so long as the water flow is above a certain minimum, it is not of much importance how much above this minimum it is, except for the slight consideration which is merited by the following reason: The temperature of the water entering the radiator (leaving the engine cylinder jackets), rather than the mean

temperature, must for operating conditions be maintained below a certain maximum, and an increase in rate of water flow may result in an increased heat transfer per degree difference between the metal and the *entering* water by raising slightly the *mean* temperature of the water. For example, if the water drops 20° in temperature during its passage through the radiator at some high rate, doubling that rate would result in a drop of only about 10°, and the mean temperature would be raised 5° for the same allowable maximum.

57. Comparison of Steam and Water as Sources of Heat for Radiator Tests.—When steam is used in the radiator instead of water the heat dissipated to the air stream per degree temperature difference is found to be practically identical with that when water is used if the "mean" temperature of the steam and condensed water in the radiator is computed, as explained in article 50, by weighting each temperature according to the specific heat or heat of vaporization involved at that temperature. The differences obtained with 10 types of radiator are shown in Table 11, compared in each case at the same air flow and with a high rate of water flow. Positive differences indicate that the heat dissipation was greater with steam than with water, and differences as high as 3 per cent are within the limit of experimental error. No reason for the larger differences has been discovered.

TABLE 11.—Comparison of Steam and Water as Sources of Heat in Radiators

Radiator No.	Average difference in heat dissipation	Radiator No.	Average difference in heat dissipation
	Per cent		Per cent
A-8	−2	C-6	+6
A-23	−1	C-7	+4
B-3	−3	D-1	+4
B-5	−5	F-5	−1
B-9	+2	G-2	−2

C. HEAT TRANSFER THROUGH THE METAL

In the conduction of heat through the metal on its way from water to air the distinction between direct and indirect cooling surface is important.

58. Direct Cooling Surface.—For direct cooling surface, where water flows along one side of a thin metal sheet and air along the other side, the flow of heat is practically straight through the sheet, and only a small temperature difference between the

two sides is needed to deliver heat as rapidly as it can be swept away from the surface by the air. The temperature drop [21] in the metal is so small in comparison with the difference in temperature between air and water that the thickness and conductivity of the metal are of small importance in heat transfer. The composition and thickness of the metal will therefore be governed by such considerations as strength, weight, liability to corrosion, cost and ease of manufacture.

59. INDIRECT COOLING SURFACE.—For indirect cooling surface thickness and conductivity of the metal are of some importance. If before being dissipated to the air heat is conducted away from the water-tube walls along a "fin" projecting into the air stream, the distance through which much of the heat must be conducted is considerably greater than the thickness of the metal, and the difference in temperature between the tip of a fin and the water-tube wall becomes of importance in lowering the mean temperature difference between air and metal. This reduction in temperature difference increases with increase in air speed, since as more heat is taken away from the surface of the fins a greater temperature difference is required to deliver the heat to the surface. The effectiveness of indirect cooling surface is considered below (art. 67).

D. HEAT TRANSFER, METAL TO AIR

The transfer of heat from metal to air depends upon temperature difference, speed and density of air, turbulence of air, and amount and character of cooling surface.

60. TEMPERATURE DIFFERENCE.—The heat dissipation from each element of cooling surface is proportional to the difference in temperature between the surface and the air to which it transmits heat. It can be shown (Appendix E), however, that if the heat dissipation of the whole radiator is proportional to the mean temperature difference between air and water it is also proportional [22] to the difference between the mean water temperature and the temperature of the air *at entrance*. If the water does not

[21] Within any limits likely to be encountered in radiators. The magnitude of this temperature drop is considered in Appendix D.

[22] Attention is directed to the fact that the relationship is proportionality and not identity. Heat dissipation expressed in terms of difference in average temperature of water and *entrance* temperature of air will obviously require a different number for its expression from the one to be used for a temperature difference obtained from average water and *average* air temperatures. The difference is not large, but is of such magnitude that the two methods of expression should be distinguished. The first form, which is used generally in this paper, is much the more convenient for intercomparisons of radiator core performance. The second form of expression is, however, necessary if the radiator is to be compared to any other form of heat-dissipating device.

change very much in temperature while passing through the radiator, an arithmetical mean of its temperatures on entering and on leaving the core will be sufficiently accurate for the mean water temperature. The difference between this mean and the temperature of the air at entrance is used throughout this report as the temperature difference under which the radiator operates.

61. Mass Flow of Air.—Measurements of heat dissipation in the reduced-pressure tunnel, with different speeds and densities of air, showed that for a given temperature difference and given radiator core the rate of heat dissipation is constant for constant mass flow of air, regardless of the particular combination of speed and density that give that air flow. The relation was tested for air densities ranging from atmospheric to a little less than half of atmospheric, corresponding to an altitude of about 7.5 km (25 000 feet), and is probably valid for somewhat lower densities. The results of the tests are shown in Table 12.

TABLE 12.—Relation of Heat Dissipation to Air Density

[Mass of air passing through core per unit time maintained constant by changing velocity inversely as density; heat dissipation in horsepower per square foot frontal area for 100° F temperature difference between entrance air and water (average); air density in pounds per cubic foot; air flow in pounds per second per square foot frontal area.]

Radiator	Air flow	Air density	Heat dissipation	Radiator	Air flow	Air density	Heat dissipation
A–8	2.08	0.0694	14.5	C–17	1.80	0.0709	13.3
		.0554	13.9			.0704	12.8
		.0457	14.1			.0363	13.2
		.0368	13.9			.0439	13.3
A–23	1.95	.0690	17.7			.0573	13.8
		.0547	17.1			.0716	13.4
		.0449	16.9			.0695	13.5
		.0363	16.9			.0552	13.8
A–34	1.80	.0681	19.6			.0467	13.5
		.0681	19.4			.0380	13.2
		.0459	19.2	D–1	2.15	.0704	12.4
		.0355	19.3			.0549	12.8
B–3	2.50	.0706	11.7			.0454	12.7
		.0558	12.0			.0357	12.3
		.0469	12.0			.0349	13.0
		.0369	12.0	F–5	1.55	.0698	14.9
B–5	2.35	.0703	11.2			.0541	14.8
		.0544	11.9			.0447	15.0
B–9	2.00	.0705	13.6			.0355	15.0
		.0554	13.1	G–2	2.00	.0710	15.1
		.0459	13.1			.0546	15.0
		.0372	13.5			.0454	15.0
C–6	2.14	.0702	14.4			.0361	14.9
		.0547	14.5	G–4	1.15	.0696	15.3
		.0458	14.5			.0542	15.5
		.0367	14.5			.0451	15.4
C–17	1.44	.0725	11.2			.0358	15.3
		.0713	11.9				
		.0712	10.9				
		.0556	11.4				
		.0456	11.2				
		.0350	10.7				
		.0348	11.4				

62. Empirical Equation for Variation of Heat Dissipation with Air Flow.—The heat dissipation for any particular type of core may be represented over a considerable range of air flow by an empirical equation with different constants for each type of core:

$$H = bM^n T \tag{1}$$

where

H = heat dissipation, metal to air, units of power per unit of frontal area,

M = air flow, mass per unit time per unit frontal area,

T = difference between temperature of the water (as a measure of that of the metal) and temperature of the entering air,

b, n = constants for each type.

Values of b and n are given in Table 21.

It should be noted that a comparison of the values of b for various types of core construction is worthless without a simultaneous consideration of n. The two constants go together in describing core performance, and the one alone is without interpretation.

63. Equation for Variation of Heat Dissipation with Depth of Core.—An equation which may be used for estimating the heat dissipation of one type of core from that of a similar type of different depth may be derived as follows. Extending the above notation, let

θ = temperature difference between water and air, both at the same distance along the air tube from the front face,

θ_0 = value of θ at front face for any air tube,

C_p = specific heat of air at constant pressure,

p = total perimeter of air tubes in unit frontal area around a section perpendicular to the direction of air flow,

x = distance measured from front toward rear of radiator,

x_1 = depth of core,

q = heat dissipation per unit surface per unit time per unit temperature difference.

Now, if it is assumed (1) that the transfer coefficient q is independent of the distance x from the front face, and (2) that the change in water temperature with depth of core is negligible in comparison with the temperature difference θ, so that the change in θ in any one air tube may be regarded as due entirely to the

rise in air temperature, then the heat gained by the air in passing an infinitesimal distance along the tubes may be placed equal to the heat dissipated by the surface past which the air has flowed, giving the equation

$$-MC_p d\theta = q\theta p dx \tag{2}$$

which, making use of the fact that $\theta = \theta_o$ when $x = o$, integrates to the form

$$\theta = \theta_o e^{-\alpha x} \tag{3}$$

where α is defined by the relation

$$\alpha = \frac{qp}{C_p M}. \tag{4}$$

The total heat transfer is given by the equation

$$H = \int_o^{x_1} q\theta p dx = qp\theta_o \int_o^{x_1} e^{-\alpha x} dx \tag{5}$$

which integrates to the form

$$H = \frac{qp\theta_o}{\alpha}(1 - e^{-\alpha x_1}) = \theta_o C_p M(1 - e^{-\alpha x_1}). \tag{6}$$

The assumption that the change in the water temperature with depth of core is negligible in comparison with other factors of the problem is equivalent to replacing θ_o by T when summing the values of θ_o over the whole cluster of tubes and averaging

$$H = C_p MT(1 - e^{-\alpha x_1}). \tag{7}$$

The coefficient α is not a constant, even for a particular radiator, because the surface dissipation coefficient q varies with the air flow; but from a single measurement of heat dissipation a value of α may be computed by equation (7) and may then be used to estimate heat dissipation at the same air flow in a similar type of core of different depth. An indication of the accuracy of this method of estimating heat dissipation may be obtained by comparing the values of the coefficient for types of radiator differing only in depth, and since for similar types α is by definition (equation 4) proportional to the heat dissipation coefficient q, comparisons may equally well be made by means of q. In Table 13 values of q taken from Table 21 are shown for groups of radiators that are nearly alike except in depth. Reference to Table 20 will show that the geometrical characteristics are not in every case quite the same, so that the validity of the equation as a change of

depth relation is probably a little better than the table indicates. An examination of equation (7) has shown that over the range of values covered a difference of a certain per cent in α (or q) introduces a difference of very nearly the same per cent in H.

TABLE 13.—Comparison of Coefficients q, Depths of Core Varying

Radiator No.	Depth		$q \times 1000$ $\left(\frac{\text{cal.}}{\text{cm}^2 \times \text{sec.} \times °\text{C}}\right)$	Radiator No.	Depth		$q \times 1000$ $\left(\frac{\text{cal.}}{\text{cm}^2 \times \text{sec.} \times °\text{C}}\right)$
	cm	Inches			cm	Inches	
A-7	12.3	4.9	3.2	B-12	8.3	3.3	3.4
A-8	6.0	2.4	3.3	B-13	10.2	4.0	3.1
A-9	7.2	2.8	3.6	B-14	7.6	3.0	3.2
A-19	7.6	3.0	3.1	B-15	10.1	4.0	3.1
A-20	12.7	5.0	3.1	B-16	10.1	4.0	3.0
A-21	7.5	3.0	3.0	C-8	12.8	5.0	3.1
A-22	10.1	4.0	3.0	C-12	25.3	10.0	3.0
A-23	12.7	5.0	2.9	C-13	20.3	8.0	3.2
B-5	5.2	2.0	2.9	C-9	10.2	4.0	3.1
B-6	8.3	3.3	2.6	C-10	10.2	4.0	3.3
B-7	10.2	4.0	2.7	C-11	10.2	4.0	3.4
B-8	13.4	5.3	2.3	C-14	20.3	8.0	3.5
B-9	8.9	3.5	3.0	G-2	4.3	1.7	4.5
B-10	6.4	2.5	3.6	G-3	8.6	3.4	4.5
B-11	7.6	3.0	3.5				

In using equation (7) as a basis for computing q from calorimetric measurements of radiator cores it is worth while to notice that the equation contains explicitly as a temperature factor the difference between the temperatures of the entrance air and average water. Accordingly, values of H may be taken directly in the form in which they are expressed elsewhere in this paper, namely, for a given temperature difference, usually 100° F or 50° C between entrance air and average water. When the conditions permit of coordinating average air temperature and average water temperature with respect to the entire cooling surface of a core, the computation of q directly from its definition is much simpler than from equation (7), avoiding the complicated arithmetic of the exponential term. The heat dissipation corresponding to any given air flow furnishes the value of the approximate rise in temperature of the air. For a simple core construction and most of the cooling surface direct a fair approximation is to assume the temperature gradients linear, and that the heat dissipation is given by considering all the metal at the average water temperature and all the air at the average air temperature, both averages being arithmetic means of entrance and exit temperatures. The total heat dissipation divided by the difference in these two average temperatures and by the total cooling surface is the value of q.

Core C–13, a circular cell construction with water surrounding every air tube, might be expected to fulfill very closely the assumptions stated above regarding uniformity of temperature and temperature gradients. The value of q computed from the heat dissipation for an air flow corresponding to a speed of 30 m per sec (100 feet per sec) through the air tube is 3.15, while the value from the exponent of the integrated equation (7) is 3.18. So nearly perfect a check is to be expected only with most favorable conditions of core construction, but for other cores it is readily possible to ascertain the approximate value of q, probably generally within 5 to 15 per cent by the short method of computing.

64. Relation Between Heat Dissipation and Surface Friction.—For estimating the heat dissipation entirely from the geometrical characteristics of a core an approximate value of the coefficient α may be obtained, which applies fairly well to types with straight, smooth-walled tubes.

It has been pointed out by Lanchester and Stanton [23] that an approximate value of the surface heat dissipation coefficient q is given by the relation

$$q = \frac{C_p R_f}{v} \tag{1}$$

where

R_f = surface friction force per unit surface,
v = linear velocity of air in tubes.

Surface friction may be estimated from the formula of C. H. Lees [24] for smooth, round tubes.

$$R_f = \rho v^2 \left[0.0765 \left(\frac{\mu}{v\rho D} \right)^{0.35} + 0.0009 \right] \tag{2}$$

where

ρ = density of air,
μ = viscosity of air,
D = diameter of tube.

Substituting equation (2) in equation (1) and equation (1) in equation (4) of article 63, which defines α, gives for the exponent αx_1 of equation (7)

$$\alpha x_1 = \frac{p\rho v x_1}{M} \left[0.0765 \left(\frac{\mu}{v\rho D} \right)^{0.35} + 0.0009 \right]. \tag{3}$$

[23] Great Britain Committee for Aeronautics Technical Report, 1912–13, p. 45.
[24] See art. 32.

The physical quantities enter in a dimensionless connection, hence the equation holds for any consistent units. Making use of the relation that mass flow of air per unit time is the simple function of density and velocitv of the air,

$$M = a\rho v$$

and

$$D = 4r$$

where

a = free area of core,
r = hydraulic radius of air tubes,

equation (3) may be put in the form

$$\alpha x_1 = \frac{px_1}{a}\left[0.0471\left(\frac{a\mu}{rM}\right)^{0.35} + 0.0009\right]. \qquad (4)$$

For surface which is all direct the factor $\frac{px_1}{a}$ may be simplified still further, thus: Since a, the free area in unit frontal area, is $A_1 + A_2 + \cdots + A_n$, the sum of the areas of the individual air tubes, and since area is perimeter times hydraulic radius, $a = p_1 r + p_2 r + \cdots + p_n r$, when the tubes are alike and r is the average hydraulic radius. But the sum of $p_1 + p_2 + \cdots + p_n$, the perimeters of the tubes in unit frontal area, is p. Hence, $p = a/r$ and $p/a = 1/r$.

Equation (4) gives the exponent of equation (7) (art. 63) in terms of the geometrical characteristics of the core, the viscosity of the air, and the air flow. By using hydraulic radius rather than diameter of tube the equation is made applicable to square and hexagonal tubes.

Equation (1) with the exponent indicated by equation (4) is applicable to types of core with direct cooling surface only, and when there is any considerable amount of indirect cooling surface a correction may be made in accordance with articles 68 and 69. When so corrected, the agreement between heat dissipation as computed and as actually measured is shown in Table 14.

TABLE 14.—Comparison of Observed and Computed Heat Dissipation

[Air flow 4 pounds per second per square foot frontal area of core]

Radiator No.	Heat dissipation $\left(\frac{\text{hp}}{\text{ft.}^2\times 100^\circ\text{F}}\right)$		Radiator No.	Heat dissipation $\left(\frac{\text{hp}}{\text{ft.}^2\times 100^\circ\text{F}}\right)$	
	Computed	Observed		Computed	Observed
A-1	31	33	B-1	15	15
A-2	38	37	B-2	21	19
A-3	21	20	B-14	20	20
A-4	19	22	B-15	26	25
A-5	27	27	B-16	26	25.5
A-6	33	31	C-1	28	24
A-7	46	43	C-4	25	23
A-8	24	23	C-5	30	29
A-9	29	30	C-8	26	26
A-13	32	27	C-9	26	26
A-15	44	42	C-10	26	26
A-16	25	23	C-11	25	26
A-17	32	28	C-12	44	45
A-19	30	28	C-13	39	39
A-20	47	43	C-14	50	50
A-21	23	21	E-6	50	49
A-22	30	28	E-7	30	30
A-23	37	33	E-8	21	23

Computed values from, $H = C_p M T(1 - e^{-\alpha x_1})$

$$\alpha x_1 = \frac{x_1}{r}\left[0.0471\left(\frac{a\mu}{rM}\right)^{0.35} + 0.0009\right]$$

H = heat dissipated (h. p.) per unit frontal area (sq. ft.).

C_p = specific heat of air at constant pressure (h. p. sec per lb. per °F.).

M = mass flow of air in pounds per second per unit frontal area. M = 4.

T = temperature difference, water and air at entrance. T = 100° F.

x_1 = depth of air tubes.

r = hydraulic radius of air tube, measured in same unit of length (any unit).

μ = viscosity of air, expressed in a unit consistent with M and r.

a = free area (a ratio, no unit).

For indirect surface a correction to x_1/r enters (see bottom p. 321).

65. Amount of Cooling Surface.—In general, increasing the amount of cooling surface (per unit frontal area) increases the heat dissipation, but if a core is redesigned with greater cooling surface the increase in heat dissipation is not, in general, proportional to the increase in the surface. Because of the rise in temperature of the air in passing through the radiator and the consequent

decrease in temperature difference between air and water, surface added by increasing the depth of the core becomes less and less effective in heat dissipation as the depth increases. If surface is added by making the air tubes smaller, the condition of turbulence in the air may be changed, and, in general, the change seems to be such as to cause an increase in the heat dissipation per unit cooling surface. Indirect cooling surface is less effective than direct, because of the drop in temperature along the metal. Spiral vanes are sometimes placed in the air tubes and furnish additional surface which, although entirely indirect, tends to increase the heat dissipation per unit surface by mixing the air stream. Whether additional surface is obtained by increase in depth, by decrease in size of air passages, or by addition of vanes, it adds to air resistance and, although increasing heat dissipation for a given air flow through the core, may decrease the air flow to such an extent that for a given flying speed nothing is gained, while much is lost because of a great increase in head resistance.

Differences either in nature or degree of turbulence of the air are indicated by the varying values of the surface cooling coefficient q of Table 21. These values are computed from equation (7) (art. 63) for such an air flow as gives a linear speed of 30 m per sec (100 feet per second) through the air tubes.

A special effect of turbulence in the air is shown in the type C–2b, which has approximately circular air tubes 20 cm (8 inches) long, with spiral vanes placed in one end extending for 5 cm (2 inches) into the tube. When the section is turned so that the vanes are in front, the heat dissipation is about 10 per cent greater for a given air flow than when they are in the rear end of the tube. The difference is shown in Fig. 27.

66. Condition of Cooling Surface.—As a general physical relation smoothness of cooling surface and its rate of heat dissipation bear too close a connection to neglect the former in considering its effects on the latter, although, as will be shown below, the differences in smoothness of metal in radiator tubes seem to fall within a range where the effect is not appreciable. A very highly polished surface shows a greater rate of heat transfer to a very high velocity air stream[25] than does one only ordinarily smooth, and in a tube the polish not only facilitates heat transfer at a given air flow but allows an increase in air flow. Conse-

[25] The fact that a high polish facilitates heat transfer at comparatively high rates of air flow past the surface should not be confused with the fact that a high polish is desirable for low heat transfer in cases where the transfer is largely due to radiation, such as the surfaces of thermos bottles.

quently, in a radiator tube this would result in a further increase in heat dissipation at a given flying speed. Surfaces usually found in radiators, however, do not differ enough in smoothness to show any very marked effect. The sections C–8 and C–9 were tested for heat dissipation both with very rough surfaces and after the surfaces had been somewhat smoothed, but the difference in heat dissipation at constant air flow was within the limit of experimental error, although the gain in air flow due to smoothing the surface (art. 21) was enough to increase the heat dissipation about 5 per cent at constant flying speed. Comparisons at constant air flow are shown on Fig. 28.

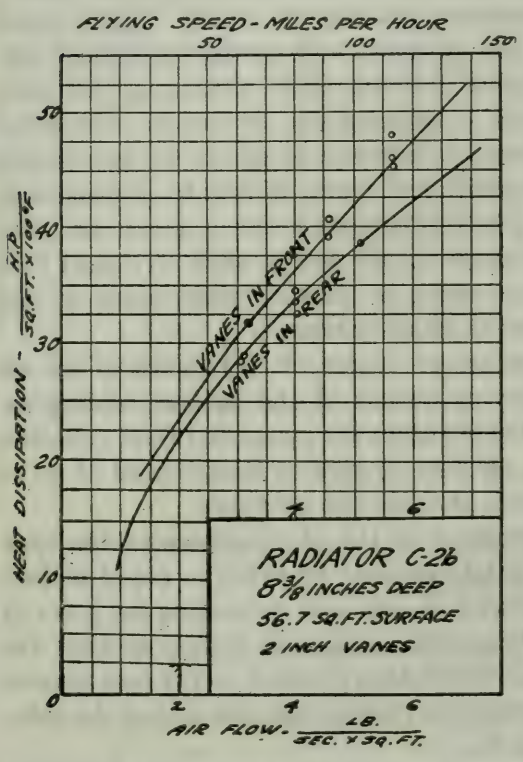


FIG. 27.—*Heat dissipation for radiator core provided with spiral vanes near one face to increase the turbulence of the air flow*

Considerable difference in turbulence and thus in heat dissipation is found according to whether or not the air stream strikes these spiral vanes immediately upon entering the core

Cleanness of cooling surface is very important. The accumulation of oil and dust sometimes found in radiator air tubes reduces the heat dissipation very greatly. A more detailed study of the effect of conditions of surface on heat dissipation was made with a single brass tube 41.5 cm (16.3 inches) long, with an inside diameter of 7.8 mm (0.31 inch), and with walls approximately 1 mm (0.04 inch) thick. Eight thermocouples were soldered into shallow slots on the outside of the tube at points 2, 7, 12, and 17 cm from the ends and heat was supplied electrically from a coil of No. 32 copper wire wound closely the entire length of the tube and insulated with baked shellac. The tube was wrapped in hair felt with a corrugated paper covering to within 1 cm of each end, and the ends were wrapped with several layers of friction tape and inserted tightly into two wooden boxes or chambers in which the

properties of the air could be measured as it entered and left the tube. These chambers were 7.6 cm (3 inches) square and 15.2 cm (6 inches) long, and each was divided into three compartments by screens. The air entering the first compartment of the inlet chamber passed through a series of screens of coarse mesh wire and finally through a thin screen of hair felt into the second compartment, where its temperature was measured. It then passed through another screen into a third compartment, into which the end of the tube projected about 1 mm (0.04 inch). This compartment was connected to one side of a vertical oil gage used to measure the pressure drop through the tube. On leaving the tube the air passed through the first compartment of the exit chamber, which was connected to the other side of the oil gage, and then through a screen of wire and a layer of hair felt into the thermometer section, and finally through another screen into the last compartment, which was connected to the inlet of the fan. The exit chamber was very carefully lagged with 2.5 cm of cork on the outside, also with 0.5 cm of hair felt on the inside, to prevent the turbulent air from striking the wooden walls directly.

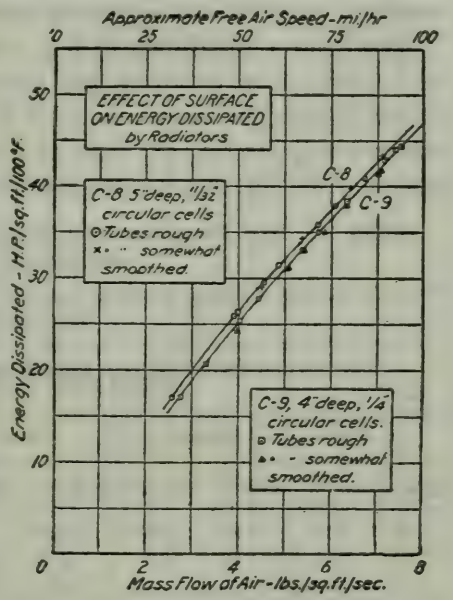


FIG. 28.—*Effect of roughness of surface on heat dissipation*

Neither radiator core shows any appreciable difference in heat dissipation at a given air flow for the two conditions of very rough and moderately smooth air tubes. At a given flying speed a small but appreciable difference would be in evidence, due to effect of roughness on the air flow (Art. 21, also Fig. 20)

The mass of air flowing through the tube was computed from the heat input to the coil, the rise in temperature of the air, and the specific heat of the air—that is, by using the tube itself as a Thomas meter—with the exception that pressure drop through the tube was used as the air meter for some of the runs after the pressure drop had been calibrated against the tube as a Thomas meter. The pressure-drop method was used in some of the earlier runs when mercury thermometers were used to measure the temperature rise, but was abandoned when thermocouples were used

for this measurement. The thermocouples were read on a "pyrovolter," and the heat input to the coil was obtained from readings of a voltmeter and an ammeter. Care was taken to obtain steady temperature conditions before beginning any set of readings.

Five conditions of service were used, namely: (1) Original surface (as the tube was drawn), (2) surface polished (considerable time and effort were expended in getting a high degree of polish), (3) polished surface lightly oiled, (4) polished surface lightly smoked, (5) surface roughened with fine sandpaper.

The results are shown in Fig. 29 and in Table 15, which shows heat dissipation in watts per degree centigrade of difference between the mean temperature of the tube and the temperature of the entering air and per cent of increase or decrease of heat dissipation over that for the original surface.

TABLE 15.—Heat Dissipation from Inside Wall of a Cylindrical Tube to High Velocity Air Stream

[Tube 0.78 cm inside diameter; air flow of 1 gram per second corresponds to approximate air speed 17.5 meters per second.]

Air flow	Heat dissipated from surface in five different conditions; also percentage differences from value for original surface (that of drawn brass tubing)								
	Original	Polished		Oiled		Smoked		Rough	
g/sec.	watts °C	watts/° C	Per cent	watts/° C	Per cent	watts/°C	Per cent	watts °C	Per cent
1	0.378	0.487	+28.8	0.447	+18.2	0.335	−11.4	0.390	+3.2
2	0.752	0.882	+17.3	0.892	+18.6	0.686	− 8.8	0.780	+3.7
3	1.10	1.28	+16.7	1.30	+18.6	0.988	−10.2	1.14	+3.6

The table shows the following: (1) The highly polished surface dissipated about 17 per cent more heat (at the higher speeds) than one fairly rough, (2) the smoked surface dissipated about 10 per cent less heat than the fairly rough one, (3) oiling the polished surface had very little effect on its heat dissipation, (4) the roughened surface was not much different in its heat dissipating qualities from the original surface.

The considerable difference in heat dissipation between the fairly rough and the highly polished surfaces may be accounted for by the fact that roughness allows a blanket of more or less stagnant air to cling to the surface, and thereby to some extent prevents the scouring of the surface that is required for the most rapid transfer of heat. The polishing was carried to an extreme entirely impracticable for radiator manufacture, and the results of the measurement may be considered to confirm those of Fig. 28,

namely, no appreciable (±3 per cent) differences in heat dissipation for roughness and smoothness as ordinarily considered in radiator surfaces.

67. Indirect Cooling Surface.—Cooling surface not backed by flowing water, called "indirect cooling surface," is less effective per unit area in heat dissipation than direct surface, but can often be used to good advantage if proper attention be given to thermal conductivity, thermal contact between the indirect surface and the water-tube walls, and shortness of the distances over which heat must be conducted through the fins. The use of indirect cooling surface amounts to closing water tube by pressing the walls together, or to substituting a single sheet of metal for a water tube (compare Fig. 62 to Fig. 61 or Fig. 60, and Fig. 83 to 84). The advantages are in saving the weight of water contained in the tube, and in the latter case the weight of one wall, while allowing relatively large free area of core for a given area of coiling surface. The disadvantage arises from the fact that heat must be transferred by metallic conduction for a distance along the fins and away from the water-tube walls before being dissipated to the air. Since heat can be conducted along the fins only with a drop in temperature, the temperature difference between metal and air is less for fins than for direct surface and decreases with distance from the source of heat. The temperature difference

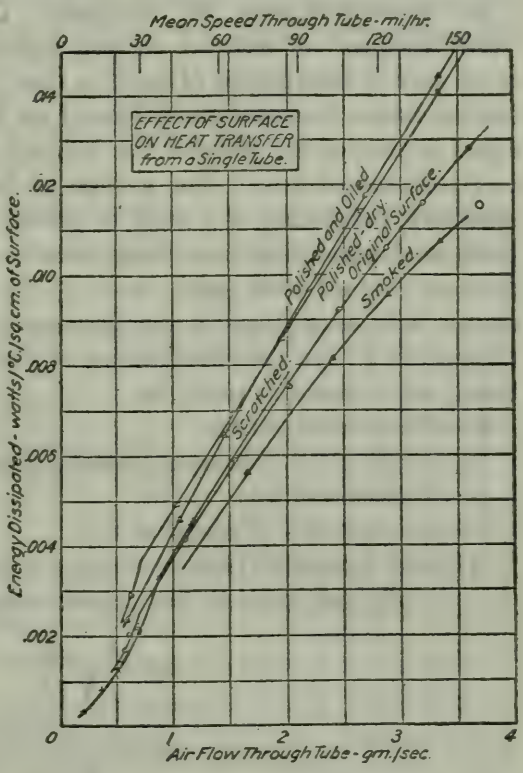


Fig. 29.—*Effect of condition of surface on heat dissipated from inside wall of a single long tube*

For the air flow corresponding to a linear velocity of 60 miles per hour in the tube (for which the flying speed of a radiator tube would be greater) the heat dissipation is increased by 15 per cent by polishing the original tube surface very highly and is decreased 10 per cent by roughening it with a smoke deposit

obviously decreases with increase in air flow, since heat dissipation increases with air flow, and greater temperature drop in the metal will be required to deliver heat to the surface as fast as it is taken up by the air. It is evident that good thermal contact is essential between the indirect cooling surfaces and the water-tube walls from which they draw heat.

68. Effectiveness of Indirect Cooling Surface.—The "effectiveness" of indirect cooling surface is defined as the ratio of its rate of dissipation of heat to that of an equal area of direct surface under the same conditions of air flow, but at a temperature equal to that of the parts of the indirect surface that are adjacent to its source of heat. For a type of fin often found in cellular radiators, consisting of a strip of metal lying between two water tubes and extending from front face to rear face of radiator, in thermal contact with one or both of the water tubes—i. e., along one or both long edges of the fin—an equation has been derived (Appendix F) for the effectiveness of the fin.

Using any consistent units, let

E = effectiveness of fin,

b = width of fin (distance between water tubes),

y = thickness of fin,

k = conductivity of metal of fin,

q = heat dissipated from fin surface in units of heat per unit time, per unit surface, per degree temperature difference.

$$u_1 = \frac{b}{2}\sqrt{\frac{2q}{yk}} \tag{1}$$

$$u_2 = b\sqrt{\frac{2q}{yk}}. \tag{2}$$

The effectiveness is found to be equal to

$$E = \frac{\tanh u}{u} \tag{3}$$

where u takes the respective values u_1 and u_2 for the case of good thermal contact along both edges of fin and the case of good thermal contact along only one edge of fin. The quantity u is dimensionless, so that any consistent units may be used in its computation. Values of the ratio $\frac{\tanh u}{u}$ are shown for different values of u on Fig. 30.

69. Computation of Heat Dissipation for Surface Partly Direct and Partly Indirect.—Differences in total heat dissi-

pated by a radiator due to differences in amount and effectiveness of indirect cooling surface may be computed as follows:

Let

H = heat dissipation of radiator,

H_d = heat dissipated by the direct cooling surface,

H_i = heat dissipated by the indirect cooling surface,

H_o = heat dissipation which the radiator would show if all the cooling surface were direct, or if the effectiveness of the indirect surface were 1.00,

r = ratio of indirect to total cooling surface,

r' = ratio of indirect to direct cooling surface,

E = effectiveness of the fins.

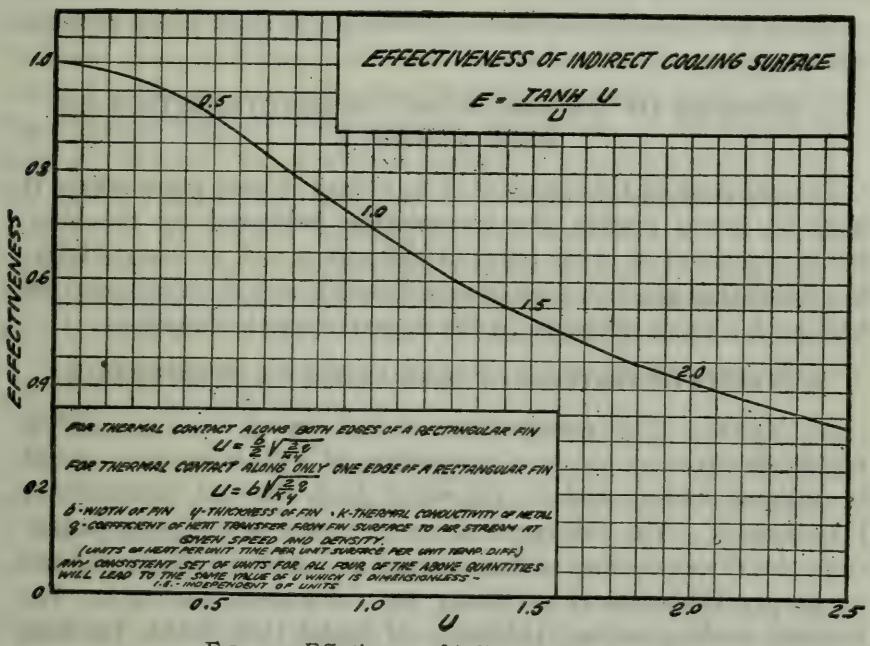


FIG. 30.—*Effectiveness of indirect cooling surface*

Ratio of heat dissipation by such surface to the dissipation by an equal area of direct surface under the same conditions of air flow but all at a temperature equal to the temperature of that portion of the indirect surface adjacent to its source of heat.

For indirect cooling surface supplied by a rectangular fin, the function U which is the abscissa of the plot is determined by the geometrical and thermal constants of the fin in the simple formula shown in the figure

Now

$$H = H_d + H_i \tag{1}$$

and

$$H_i = Er'H_d \tag{2}$$

so that

$$H = H_d(1 + Er') \tag{3}$$

Also

$$(\text{if } E = 1),\ H_o = H_d(1 + r'). \tag{4}$$

Then, the ratio of heat dissipated by the radiator to that which would have been dissipated were all the surface direct is

$$\frac{H}{H_o} = \frac{1 + Er'}{1 + r'} \tag{5}$$

Substituting

$$r' = \frac{r}{1 - r} \tag{6}$$

$$\frac{H}{H_o} = \frac{1 + E\frac{r}{1-r}}{1 + \frac{r}{1-r}} = 1 - (1 - E)r \tag{7}$$

An assumption of indirect cooling surface as high as 60 per cent of the total and the effectiveness as low as 90 per cent would give for this ratio 0.94.

V. EFFECTS OF GEOMETRICAL CHARACTERISTICS ON PERFORMANCE

The purpose of this chapter is to collect in one place where it may be found readily the information indicated by the title. Some repetition of other parts of the report will be unavoidable, but items that are discussed in detail elsewhere will be summarized here with a cross reference to the more complete discussion.

A. EFFECTS OF FEATURES OF CORE DESIGN ON PERFORMANCE

70. METAL.—The composition of the metal has an entirely negligible effect on the heat dissipation of a radiator core, except in indirect cooling surface, for which high thermal conductivity is important. The thickness of metal is also of negligible importance for direct-cooling surface, except as it adds to the weight and as proper thickness is necessary for mechanical strength. For indirect cooling surface thickness of metal is desirable for heat transfer but undesirable because of weight. The composition and thickness of the metal must be governed very largely by considerations not taken up in this report, such as mechanical strength, durability, and ease and cost of construction and repair. Such thermal considerations as do enter (indirect surface) are discussed in articles 67–69 and 75.

71. WEIGHT.—Weight of the core should evidently be the minimum that is consistent with such governing conditions as thickness of metal and thickness of water streams. In comparison with head resistance it is of rather great importance at low speeds but little importance at high speeds (see art. 44).

72. Free Area.—For unobstructed positions of a radiator a large free area is desirable in order to increase air flow and decrease head resistance and should be sacrificed only for the sake of compactness of the radiator. Care taken in making the water tubes as narrow as is consistent with sufficient strength and space for ample water flow is repaid by an increase in figure of merit. For use in obstructed positions, where head resistance of the core is relatively unimportant, high free area can well be sacrificed (see arts. 23, 41).

73. Amount of Cooling Surface.—A large amount of cooling surface per unit frontal area is desirable for high heat dissipation at a given air flow, but can be obtained only at the expense of reduction in free area and air flow and increase in head resistance. The heat dissipated per unit frontal area is not in general proportional to the amount of cooling surface because of (1) smaller temperature difference between air and water at the rear face than at the front, (2) smaller temperature difference between air and metal for indirect than for direct cooling surface, and (3) changes in turbulence with change in construction. Indirect cooling surface can often be used to good advantage on account of its saving in weight and its relatively small reduction of free area, but attention must be given to thermal conductivity, thermal contact with the water tube walls, and proper proportions of fins (see arts. 67–69, and art. 75).

74. Condition of Cooling Surface.—Cooling surfaces in radiators should be kept clean. An accumulation of oil and dust on the surface will have a very harmful effect on the performance of the radiator. The following remarks apply only to conditions in which the cooling surfaces are reasonably clean:

(*a*) Heat dissipation from an ordinarily smooth surface to a high-speed air stream may be increased 17 per cent for a given air flow by giving the surface extremely high polish, or it may be decreased 10 per cent or more by roughening the surface with a layer of smoke deposit.

(*b*) Surfaces likely to be obtained in radiators, if fairly clean, will not differ in smoothness enough to give appreciable difference in heat dissipation with a given flow of air through the core.

(*c*) Heat dissipation from a radiator at a given airplane speed may be slightly increased if special attention be given to smoothness of surface, because this results in a small increase in the air flow through the core.

(*d*) Heat dissipation to a high-speed air stream is practically unaffected by a light coating of clean oil on a smooth surface.

(*e*) Pressure gradient in the air flowing through a radiator tube of simple geometrical form is practically independent of the roughness of the surface over a considerable range.

(*f*) Pressure gradient in such a tube is practically unaffected by a light coating of clean oil on a smooth surface.

(*g*) Head resistance of a radiator may be decreased slightly by polishing the surfaces (8 per cent observed in one case).

(*h*) Figure of merit of a radiator may be somewhat increased by polishing the surfaces.

(*i*) In general, the performance of a radiator may be improved a little by polishing the surfaces, but if they are fairly smooth and clean a considerable polish is required to produce much change in the properties of the radiator, and there is a question whether or not such a method for improvement be practicable.

75. Proportions of Fins for Given Effectiveness.—Since the effectiveness of indirect cooling surface is determined by the function u, developed in article 68, equation (2) of that article may be solved for y, giving

$$y=\frac{2b^2q}{u^2k}, \tag{8}$$

which shows that the thickness of fin resulting in any given effectiveness is directly proportional to the square of the width, to the coefficient q, which varies approximatley as the 0.8 power of the air flow, and inversely proportional to the conductivity of the metal. If the fin is formed by folding the metal over, the thickness of fin includes both thicknesses of metal. Table 16 shows the approximate thicknesses of fin that will give effectiveness of 90 and 95 per cent with different widths. The table is computed for a long, narrow fin of rectangular form, soldered or continuous with the water-tube walls on only one edge. If both edges are in good thermal contact with the walls, the thickness may be divided by four.

If the coefficient q is not known for a certain type of radiator, it may be estimated by means of equations (1) and (2) article 64. In order to show the magnitude of the effectiveness of ordinary indirect cooling surface, a computation has been made for a type similar to the radiators A 7, 8, 9, 13 (Figs. 57–60), assuming 50 per cent indirect cooling surface. In this case the effectiveness is found to be 94 per cent at an air flow of 4.3 pounds per second per square foot frontal area, or a flying speed of about 70 miles per hour (31 m per sec), and 91 per cent at an air flow of 8 pounds, or a flying speed of 130 miles per hour (60 m per sec).

The reduction in heat dissipation due to the fact that the indirect cooling surface is less effective than the direct is 3 and 4 per cent for these two cases.

TABLE 16.—Thickness (in Inches) of Indirect Radiator Fins of Brass or Copper for Different Widths and Air Speeds to Give Effectiveness of 90 Per Cent and of 95 Per Cent

[For thermal contact along one edge only. If both edges of fin make good thermal contact with source of heat, divide thickness by 4]

Width of fin (inches)	Copper fins				Brass fins			
	Thickness to give effectiveness of 90 per cent at air speeds of—		Thickness to give effectiveness of 95 per cent at air speeds of—		Thickness to give effectiveness of 90 per cent at air speeds of—		Thickness to give effectiveness of 95 per cent at air speeds of—	
	150 mi./hr.	60 mi./hr.	150 mi./hr.	60 mi./hr.	150 mi./hr.	60 mi./hr.	150 mi./hr.	60 mi./hr.
0.250	0.0068	0.0032	0.015	0.0072	0.025	0.012	0.052	0.026
.375	.016	.0076	.034	.016	.056	.026	.12	.056
.500	.028	.013	.060	.029	.100	.048	.21	.104
1.000	.112	.052	.24	.12	.40	.19	.85	.41

76. Depth of Radiator.—Increasing the depth (dimension parallel to the direction of air flow) of a particular type of radiator increases its heat transfer for a given air flow by increasing the cooling surface, but the added surface becomes less effective as the depth is increased on account of the rise in temperature of the air in its passage through the radiator and the consequent decrease in temperature difference between the air and the water. Furthermore, resistance to air flow increases with increase in depth, so that the air flow at a given flying speed is less. An increase in depth is accompanied by an increase in head resistance, weight, and power absorbed, but at the smaller depths the disadvantage of the increased absorption of power is less than the advantage of the increased heat dissipation, and the figure of merit rises to a maximum at a certain depth which varies with the type of core and with the speed of flight.

In order to show the effect of depth on performance, estimates have been made for various general types of radiators by means of the empirical equations as a medium for averaging the experimental data obtained from measuring individual radiator cores, differing slightly but of one general type in each case. The average performance curves for a number of types are shown in Figs. 31 to 34. Air flow was estimated by using empirical equa-

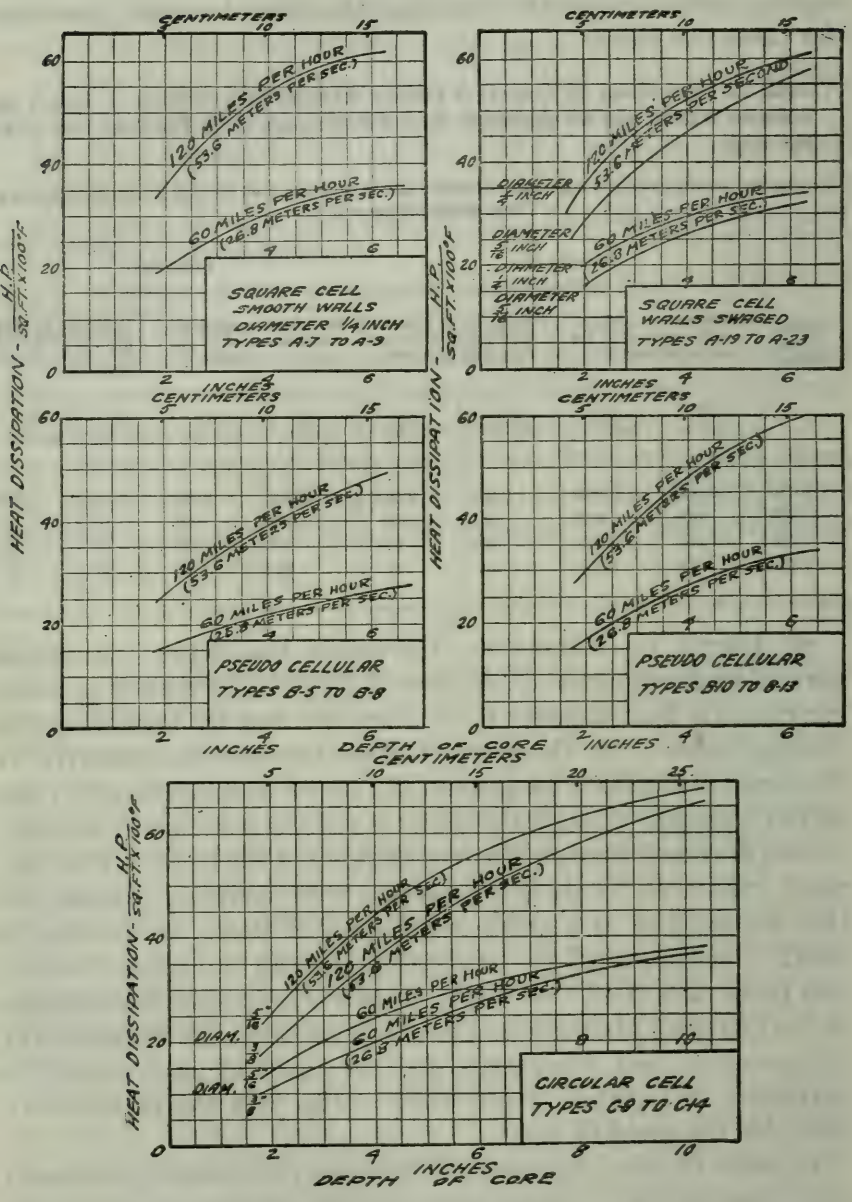


FIG. 31.—*Relation between depth of radiator core and heat dissipation, other conditions being constant*

The deeper the core, the less does an additional inch of depth add to its heat dissipating ability, as indicated by the flattening of the curves toward the top. (This characteristic is, however, little in evidence for usual depth of a core with very low heat dissipation for given flying speed, such as B–5 to B–8)

tion (1) of article 20, and heat dissipation by using equation (7) of article 63, taking in each case mean values of empirical constants computed from laboratory measurements with radiator cores of the type considered and mean values of geometrical characteristics for each different group.

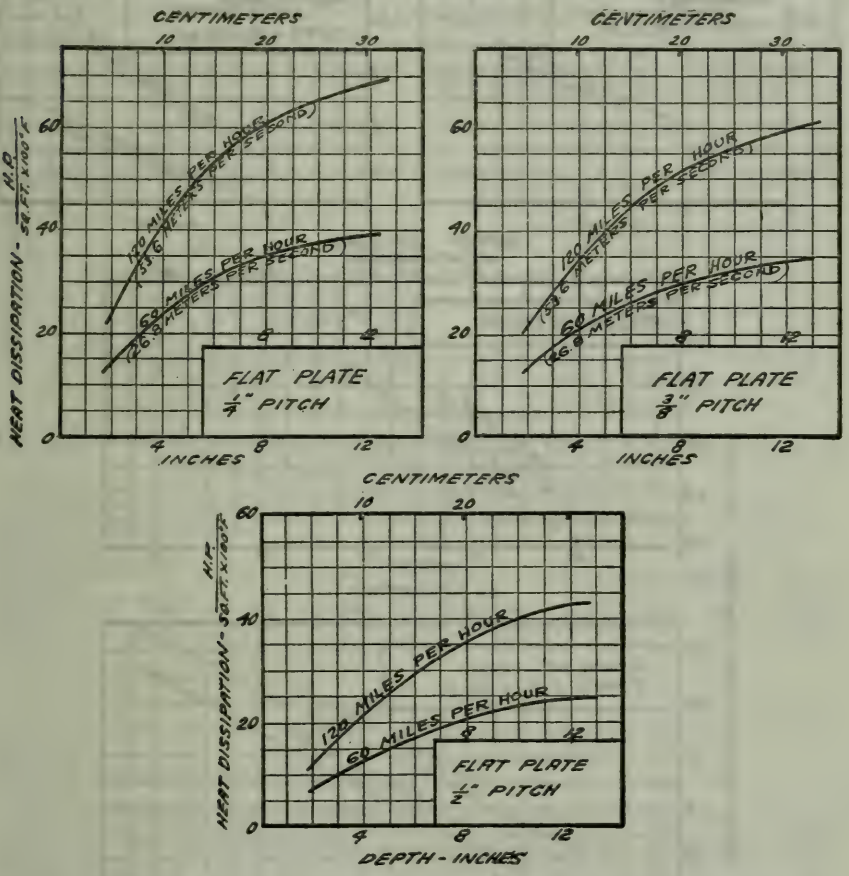


FIG. 32.—*Relation between depth of radiator core and heat dissipation for flat plate cores*

Curves show general trend exactly similar to those for cellular radiators plotted in Fig. 31

In applying equation (7) of article 63, namely,

$$H = MC_p T(1 - e^{-\alpha z_1})$$

to this computation the following points require consideration. As noted in article 63, the factor α, defined by the relation

$$\alpha = \frac{qp}{MC_p} \qquad \text{(equation 4, art. 63)}$$

is not a constant even for a particular type of radiator because of the variation of the quantity q with changes in air flow. To reduce the labor of computing, it is very desirable to have a con-

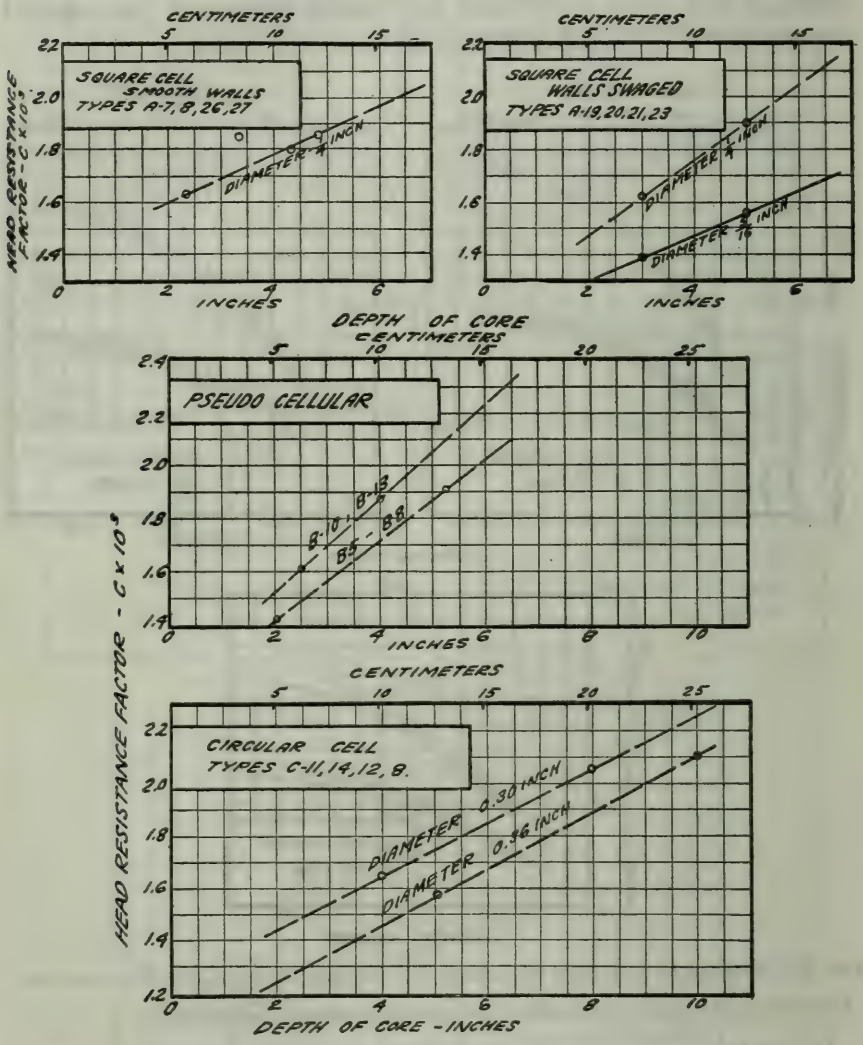


FIG. 33.—*Effect of depth of radiator core on head resistance at any given speed*

Head resistance factor is the head resistance per unit frontal area (lbs. per square foot for above curves) divided by the square of the flying speed (miles per hour) and is therefore nearly independent of speed. The curves indicate a linear relation between this factor and depth of radiator core. Since heat dissipation does not increase so rapidly as core depth (Figs. 31–32) some optimum depth may be found for each set of conditions. See Figs. 35–36

stant for the particular core in the exponent of e in the equation written above, and this is secured by introducing the empirical relation (art. 62 and Table 21), that when all other conditions are

constant the heat dissipation of such cores varies approximately as the 0.8 power of the air flow, and q is proportional to the heat dissipation.

Accordingly, for the purpose of these computations, it was assumed that q varies in that manner except in the case of the flat plate radiators, for which the exponent was separately determined from the tests on each section. Thus, q varies as $M^{0.8}$ and α varies as $M^{0.8}/M$ or as $M^{-0.2}$. Combining all the constants of

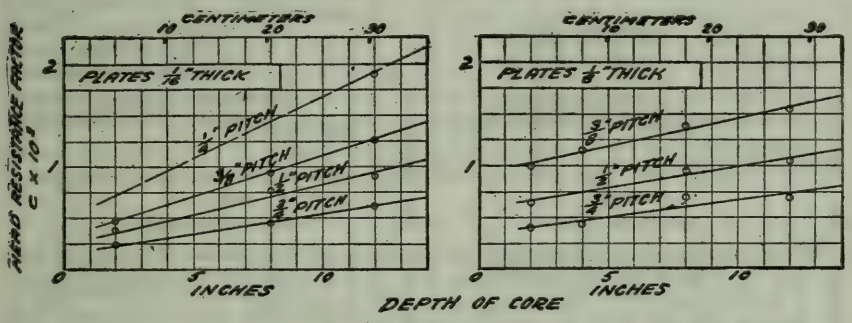


FIG. 34.—*Laboratory measurements of head resistance factor for flat plate radiator cores of several depths, pitches, and plate thicknesses*

The results show that over the range of depths measured, increase in head resistance is strictly proportional to increase in depth of core

proportionality into a single constant β, the computation for a given core with everything constant except air flow and depth reduces to tabulation of the product

$$MC_pT\left(1-e^{\beta\frac{x}{M^{0.2}}}\right)$$

for the several values of M and x.

For estimates of head resistance at various depths of a type core from measurements made on individual cores of the type nearly alike in other characteristics, although not identical, it was assumed that for depths greater than a certain value the resistance may be regarded as the sum of two parts—one due to eddy resistances at the front and rear faces and the other to internal resistance in the core—so that an increase in head resistance caused by increasing the depth would be proportional to the increase in depth. This assumption is supported by the results of the tests on flat plate radiators of depths from 5 to 30 cm (2 to 12 inches), which indicate that the lower limit of the range over which the assumption is valid is less than 5 cm (2 inches) of depth. Results obtained with the flat plate radiators are shown

in Fig. 34, and Fig. 33 shows the basis of estimates for other types. In computing figure of merit the weight was assumed to increase uniformly with increase in depth.

The curves of Figs. 35–36 show (1) that the best depth for use in obstructed positions—i. e., the depth giving maximum figure

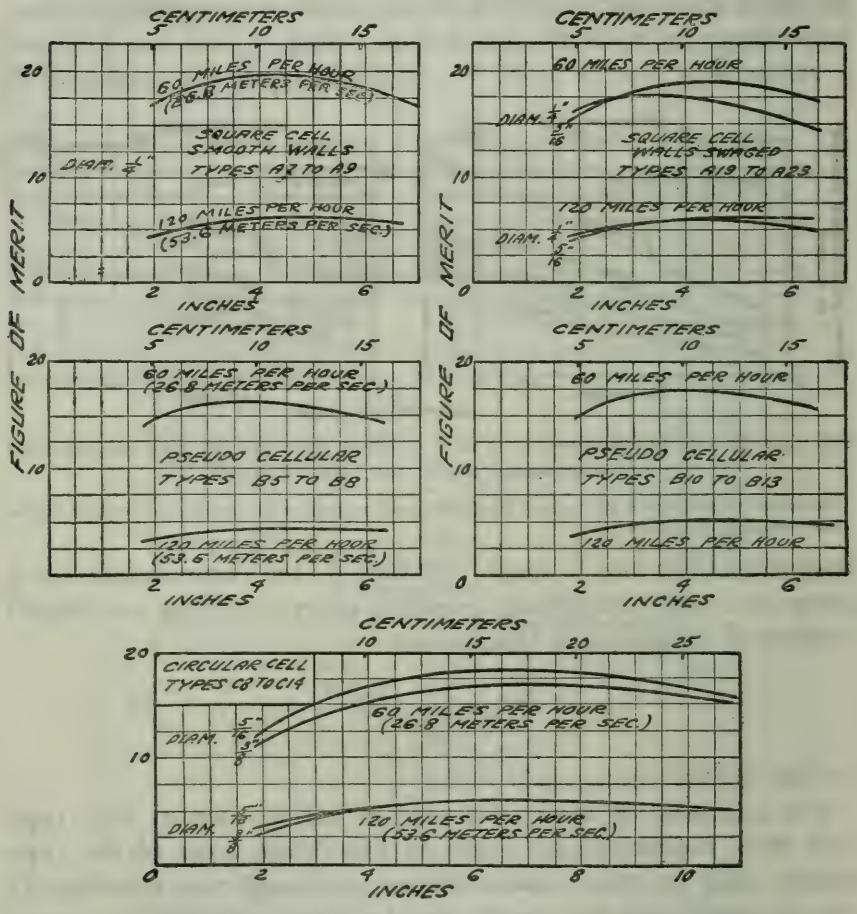


FIG. 35.—*Relation between depth of radiator and figure of merit of cellular cores*

Figure of merit is the ratio of power dissipated as heat to the engine power absorbed by the core in overcoming head resistance and sustaining its weight. It is therefore a measue of relative merits of radiator cores in unobstructed positions. The curves show that there is an optimum depth for given flying speed

of merit—is greater for high speeds than for low, and (2) that a small excess of depth over the optimum causes slightly less decrease in figure of merit than does an equal deficit of depth, so that an error in design on the side of too great depth is perhaps to be preferred to one on the side of too small depth. Figures for most efficient depths for the various types are collected in Table 17.

TABLE 17.—Most Efficient Depth of Radiator Core for Use in Unobstructed Position

Type of core	Optimum depth at flying speed of—	
	60 miles/hr.	120 miles/hr.
	Inches	Inches
Square cell, smooth walls, diameter ¼ inch	4	4–6
Square cell, walls swaged, diameter ¼ inch	3–4	4–5
Square cell, walls swaged, diameter $\frac{5}{16}$ inch	4–5	4–6
Pseudocellular, hexagonal (B–5 to B–8)	3–4	4–6
Psuedocellular, hexagonal (B–10 to B–13)	4	4–6
Circular cell, diameter 0.36 inch	6–8	6–8
Circular cell, diameter 0.30 inch	6–7	6–8
Flat plate water tube, pitch ¼ inch [a]	4–5	5–7
Flat plate water tube, pitch ⅜ inch	4–6	5–7
Flat plate water tube, pitch ½ inch	4–6	6–8

[a] Measured across front, center to center of plates.

77. Form and Dimensions of Water Passages.—Conditions for minimum absorption of power in pumping water through the radiator would evidently require that the water passages should be straight, with smooth walls and large cross sectional area; but the power used in driving the pump is a very small part of the engine power, and the best conditions for the pumping may well be sacrificed for those that facilitate the best relation between heat dissipation and head resistance. The thickness of the streams of water should be as small as is consistent with sufficient flow under reasonable pressure difference and security from obstruction by particles in the water, in order that the free area may be as large as possible and the head resistance and weight of water as low as possible. Pockets in the water passages in which the water is comparatively stagnant should be avoided because their heat transfer is low, they add unduly to the weight of water, and they occupy space that might better be left open for the flow of air. Cooling surface around such pockets has been rated as indirect in this report.

78. Form and Dimensions of Air Passages.—For use in unobstructed positions it is important that the air passages should be straight and as smooth as practicable to facilitate air flow and reduce head resistance. Projections, indentations, and holes in the air-tube walls add greatly to the head resistance without causing a corresponding increase in heat transfer. The slight advantage of saving in metal gained by punching holes in the indirect cooling surfaces is more than outweighted by an increased head resistance and a change in turbulence of the air which,

although it may increase the heat dissipation per unit cooling surface for a given air flow, reduces the air flow to such an extent that the heat dissipated for a given flying speed may be actually reduced. In general, all surfaces past which air flows should be continuous from front to rear of the radiator to give a maximum of effective surface with a minimum air resistance, because at every point where there are discontinuities in the surface eddy resistances are introduced. The head resistance of "fin and tube" types is very high for just this reason. The material summarized in this paragraph is discussed in detail in article 38.

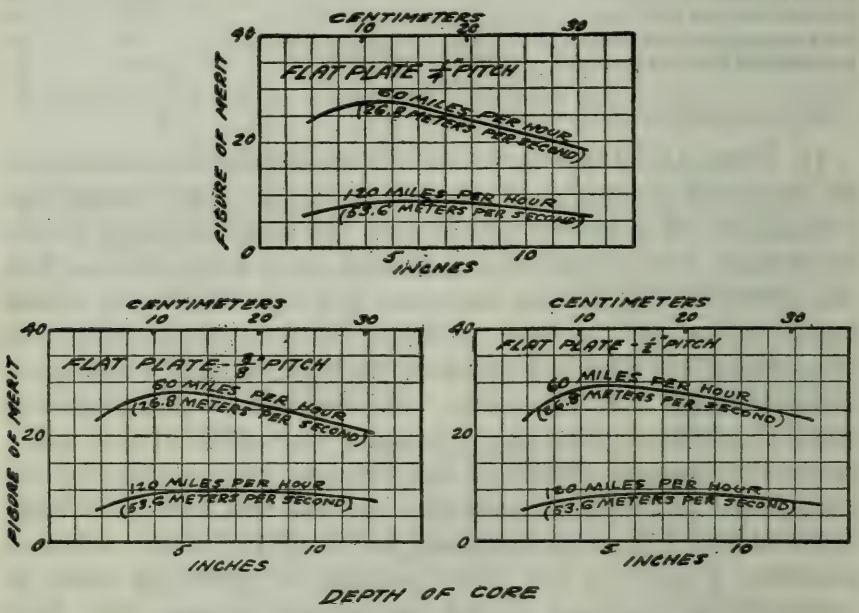


FIG. 36.—*Relation between figure of merit and depth of radiator for flat plate cores*

Curves show similarity to those of Fig. 35, for cellular cores. Differences in scale of abscissas account for the fact that the maxima appear to be more sharply defined than in Fig. 35

The use of spiral vanes, or other devices for increasing turbulence, although often increasing the heat transfer per unit cooling surface at a given air flow, is detrimental to the general performance of the radiator for use in unobstructed positions but advantageous in some cases for use in obstructed positions. For a comparison of square, circular, hexagonal and other types of air tubes see below, "Special types of radiators" (arts. 79 et seq.). In considering the effects of turbulence and turbulence devices on the performance of the radiator it is necessary to bear in mind the importance of the quantity of air flowing through the core and the fact that at a given speed of flight rather widely different

amounts of air flow through different radiators. Any form of construction that imparts additional turbulence to the air may be expected to increase the resistance to flow of air and consequently to decrease the flow through the radiator for a given flying speed, while at the same time increasing the head resistance. If, then, there is to be a gain in general performance, the turbulence device must, by increasing the amount of cooling surface or by causing the air to scour the surface more thoroughly, or both, increase the heat dissipation enough to overbalance both the decrease in amount of air flow (which tends to decrease the heat dissipation) and the increase in head resistance.

The general performance of four types of radiator, each representing one of the best of its class, is shown in Fig. 37 by the "figure of merit," which is the ratio of the rate of dissipation of heat (expressed in units of power) to the power absorbed in overcoming the head resistance and sustaining the weight of the radiator. It is noticeable that at the usual flying speeds the flat plate and square cell types show much higher figure of merit than the other two types, although at a speed of 9 m per sec (20 miles per hour) the type with spiral vanes would probably be better than even the flat plate type. The figures of merit as drawn apply only to radiators mounted in "unobstructed" positions, such that flow of air through and around them is practically unaffected by other parts of the aircraft. For use in such positions at high speeds every form of turbulence device known to the authors is detrimental to the general performance of the radiator. On the other hand, if a radiator is to be used in such a position as the nose of the fuselage, the air flow through it at best is low and can not be increased without undue increase in head resistance of the combination of fuselage and radiator. In this case heat must be transmitted as rapidly as possible to the small amount of air that does flow through, and it may be profitable to use turbulence devices. It is possible that the rate of heat dissipation for the whole radiator may be increased, while added air resistance of the core may actually reduce the head resistance of the fuselage and radiator.

B. SPECIAL TYPES OF RADIATORS

Of the general classes into which radiators may be divided those with flat plate water tubes show the greatest figures of merit at high speeds in unobstructed positions. Comparison of different types may be made by the use of Table 21.

79. CELLULAR TYPES.—The cellular types of core vary rather widely in performance, even between types with the same form of cell; but of the radiators tested the best of the square cell types are better than the others, with the separate air tube types (circular and hexagonal) ranking second. The circular cell type has

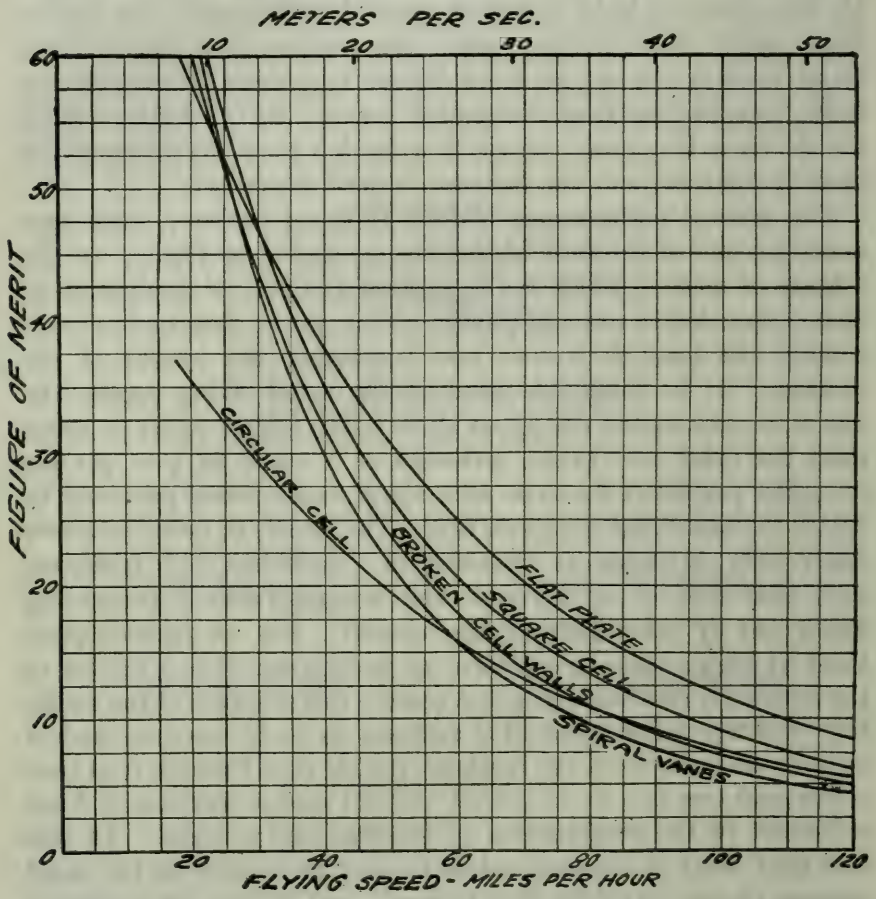


FIG. 37.—*Figure of merit of typical radiator cores in unobstructed position*

Ratio of power dissipated as heat to power absorbed in overcoming head resistance and sustaining the weight. A measure of comparative merits of the several types at any given flying speed. The curves show that devices to increase turbulence in the air tubes of a radiator (spiral vanes, broken cell walls, etc.) are detrimental in unobstructed positions for all customary flying speeds

been largely used by both the American and British Governments, not because they have the highest figure of merit, but principally because of such other considerations as ease of repair.

80. FLAT PLATE TYPES.—Radiators whose water tubes are plain hollow plates continuous from front to rear of the core and with no indirect cooling surface show higher figure of merit at high

speeds than any other form that has been tested. While the plates are mechanically weak, the advantages in performance are so great as to merit special study, and the types E–6, E–7, and E–8 (Figs. 109–111) have been used as a basis for estimation of the properties of similar types of other depths.

Computations were made as outlined in article 76, using empirical constants computed from measurements for these three types. For head resistance a set of 22 dummy radiators was constructed using depths of 2, 4, 8, and 12 inches, spacings from center to center of plate of one-fourth, three-eighths, one-half, three-fourths, and 1 inch, and thicknesses of one-sixteenth and one-eighth inch (depths 5.1, 10.2, 15.2, and 30.5 cm, spacings 0.63, 0.95, 1.27, 1.91, and 2.54 cm, thicknesses 0.16 and 0.32 cm). The plates were made by covering cardboard of the proper thickness with thin sheet copper, and the same plates were used repeatedly. They were 12 inches long, and, with the exception of the one-fourth inch spacing, enough were used to make a radiator approximately 1 foot wide. The surfaces were not as smooth as might have been desired, but were fairly representative of what is found in commercially manufactured radiators.

The measurements of head resistance are recorded in Table 30 of Appendix G. It was found that for plates one-sixteenth inch (0.16 cm) thick the head resistance factor c (applicable to the equation $R = cS^2$ at speeds near 60 miles per hour) for the English units was well represented by the equation,

$$c = n(1.0 + 2.5x)(10^{-5})$$

where c = head resistance factor (for 60 miles per hour).
n = number of plates per foot width of core,
x = depth of core, inches.

The agreement between this equation and the observed data is indicated on the left half of Fig. 34, in which the lines represent the equation and the circled points the observations. Weight of the core was estimated from geometrical considerations, and the densities of copper and solder to be

$$w = 0.056\ nx$$

where w = weight of core and contained water, pounds per square foot frontal area.

In Fig. 32 the heat dissipation and in Fig. 36 the figure of merit are shown in terms of depth of core. The curves show that the wider spacings are a little better than the narrowest, although

there is not much difference in figure of merit between the three-eighths and one-half inch spacings. The flatness of the figure of merit curves at the higher speeds shows that if considerations of compactness make it desirable to increase the depth over the optimum value this can be done without much sacrifice in figure of merit. The flat plate types are characterized by high air flow and low head resistance for a given flying speed and by high figure of merit at the greater speeds.

81. Fin and Tube Types.—In general, fin and tube types are characterized by high head resistance and low air flow and partly by the large amount and often the low effectiveness of the indirect cooling surface. The form of construction gives large eddy resistance, because each water tube is subjected to impact on one side and suction on the other, with the result that the total (projected) area subjected to impact and suction on all the tubes is much greater than that necessitated in a cellular radiator of the same size or cooling surface.

Excessive head resistance, accompanied by low heat dissipation, makes the fin and tube types unsuitable for use on an airplane where they will be exposed to a current of air at high speed. The more compact types, however—notably F–4, which has large water tubes with crimped spiral fins nearly touching each other—show a relatively high heat dissipation at very low air flows, which justifies their use on trucks and automobiles other than racing cars.

Figs. 38 and 39 show heat dissipation of five types in terms of air flow through the core and in terms of flying speed in unobstructed positions for the types of fin and tube construction for which the air flow constant has been measured. No air flow constant was found for F–3 because of damage to the section before the measurement was completed, and none is given for F–4 because the air flow was too low to be measured by the air venturi meter.

The only type for which head resistance was measured is F–6, which is similar to F–5, except that its depth is not quite so great. In order to give some indication of what figure of merit may be expected from a fin and tube type, the head resistance and power absorbed for F–6 have been combined with the heat dissipation and air flow of F–5 in computing the curves shown in Fig. 115. This, of course, gives the figure of merit slightly higher than the type F–5 would give, but even with an error on the side of good performance the result shows that the type is not suitable for

general aeronautic use. It is possible that for a wing position, where the air flow is low and head resistance *of the core* is not a detriment, a fin and tube radiator could be used.

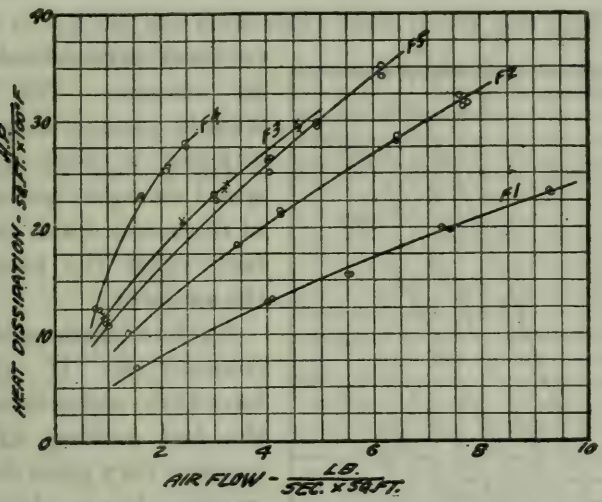


FIG. 38.—*Heat dissipation of fin and tube radiators as a function of air flow through core*

F–1 and F–2 are similar except that fins on F–2 are spaced only half as far apart as on F–1. F–3 has fins of same spacing as F–2, but the water tubes are much smaller and closer, raising effectiveness of fins. F–4 has water tubes closely packed in comparison with the others listed above, and a relatively narrow spiral fin girdles each tube

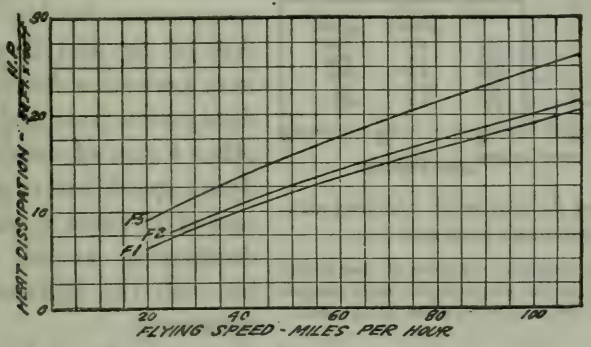


FIG. 39.—*Heat dissipation of fin and tube radiator core in terms of flying speed*

Comparison with Fig. 38 shows that the great difference in heat dissipation of cores F–1 and F–2 for the same air flow through the core makes little difference in effective heat dissipation, the reason being that the closer fin spacing of F–2 cuts down the air flow so much more that at given flying speed the resultant effect of the two cores is nearly the same

82. WHISTLING TYPES.—Three general types of construction have been found to cause the radiator to whistle in an air stream. The three classes are (1) plain water tubes separated from each other, E–9, (2) perforated water tubes separated from each other,

E–1 to E–5, and (3) corrugated plates, with air flowing across the corrugations, E–10.

The form of construction leaves passages *across* the air tubes in which are short columns of air over the ends of which air is blowing, with the result that vibrations are set up in the short columns perpendicular to the air streams. The resulting whistle varies widely in intensity and in pitch as the air speed changes, and conditions of resonance have marked effects upon the properties of the radiator.

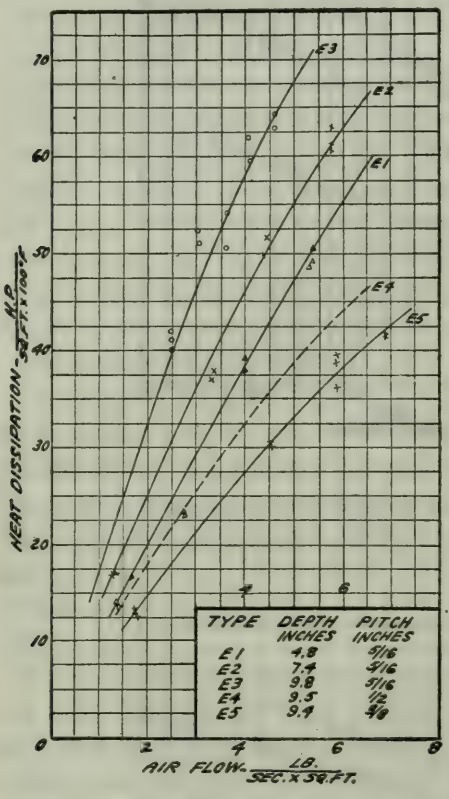


FIG. 40.—*Heat dissipation of whistling radiators—perforated water tube type*

Although heat dissipation for given air flow is high, the type is not good for use in unobstructed positions because of very low air flow for given flying speeds

By the vibrations of the cross columns air is alternately forced into and withdrawn from the fast moving stream and causes a very great drag on the stream. As a result the air flow for a given flying speed is very low and the head resistance is very high. The very great turbulence in the air flow tends to compensate for the decreased flow of air, and in some cases may prevent a decrease in heat dissipation from the value for other forms of core at a given flying speed, but in no case observed is there a gain in heat dissipation at all comparable with the increase in head resistance.

The heat dissipation in terms of air flow is shown for the types E–1 to E–5 in Fig. 40, the curve for E–4 being obtained by interpolation[26] between E–3 and E–5. The complete properties of the other types are shown in the series of general plots of properties (Part VII, art. 109). The superiority of the flat plate (continuous from front to rear of core) type over the whistling types is indicated by the comparisons made in Table 18.

[26] In the types E–3 and E–5, which are of the same depth as E–4, but with different pitch, the heat transfer was found proportional to the number of plates per unit width of core, and this proportionality was used for interpolation.

TABLE 18.—Comparison of Flat Plate and Perforated Plate Radiators

Type	Characteristics	Depth	Pitch	Cooling surface per unit frontal area of core
		Inches	Inches	Ratio [a]
E-4	Perforated plate (whistling)	9.5	0.5	29
E-8	Flat plate	9.75	.5	39

[a] Ratio (square feet per square foot) independent of unit.

Properties at Flying Speeds of 60 and 90 Miles Per Hour (1 Square Foot Frontal Area)

Properties	60 mi./hr.		90 mi./hr.	
	E-4	E-8	E-4	E-8
Air flow, pounds per second	2.63	3.79	3.94	5.68
Heat dissipation, horsepower per 100° F.	23.3	22.3	32.3	30.6
Head resistance, pounds	6.7	3.0	15.0	6.6
Power absorbed, horsepower	1.75	.89	4.62	2.20
Figure of merit	13.3	25.0	7.0	13.9

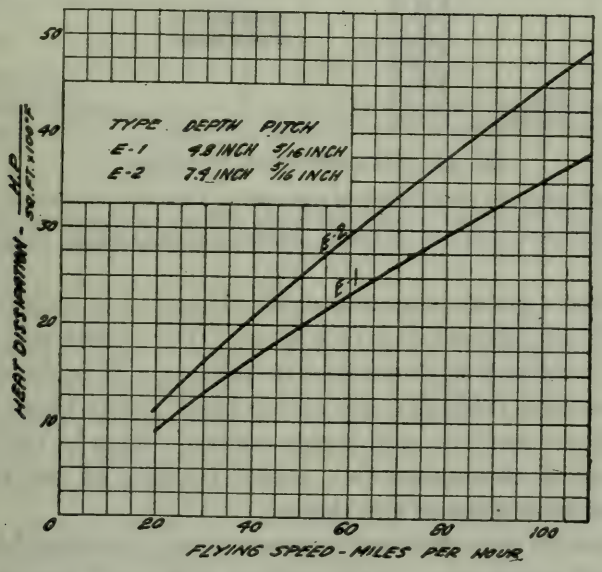


FIG. 41.—*Heat dissipation of whistling radiators (perforated tube type) in terms of flying speed*

83. WING AND STRUT SURFACE.—Various devices have been suggested, such as using the underside of the wing for the cooling surface or building the struts and other parts of the airplane with double walls and passing water through the spaces formed. While such construction might furnish heat transfer with no great increase in head resistance, it involves mechanical difficulties in

construction. It is essentially heavy because of the two walls necessary to confine the water streams; only one is available for effective cooling surface. Furthermore, to keep frictional resistance (water) within reasonable limits the water streams must be fairly thick on account of their great length. The construction would obviously be unsuitable for military use because of its vulnerability. Such surface would probably be slightly less effective in dissipating heat than would an equal area of cooling surface made up into a good form of radiator.

84. Stream-Line Casing for Radiator.—It has been suggested that a stream-line casing around a radiator might improve its performance by reducing head resistance, and a limited study has been made of the effect of such a casing. The radiator used

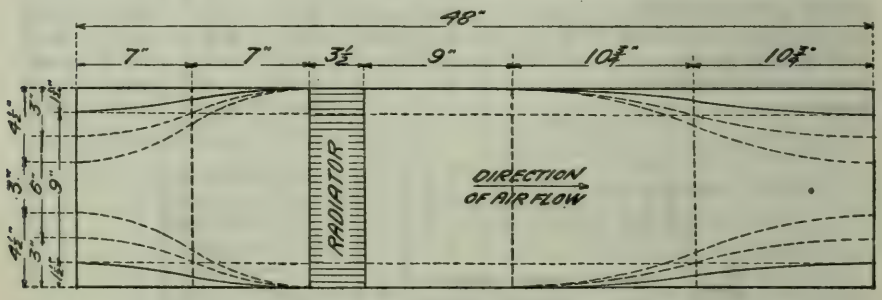


Fig. 42.—*Stream-line casing for radiator*

The sides of casing are curved, top and bottom of casing plane. The curved sides were set in each of the three positions shown. The stream-line casing reduces head resistance very greatly and reduces air flow through the radiator, and therefore heat dissipation. The net result under different conditions is shown in Fig. 44

was a 12-inch (30 cm) square section of core of ¼ inch (0.63 cm) square cells 3⅜ inches (8.6 cm) deep. The casing was made of galvanized iron and is illustrated in Fig. 42. It is stream lined in one dimension only, the top and bottom pieces being flat rectangular sheets and the side pieces curved. Arcs of circles were used instead of the stream-line curves because of the fact that air flows on both sides of the sheet.

Fig. 43 shows that the casing causes a very considerable reduction in head resistance. With certain widths of mouth it also greatly reduces the air flow through the core. As the side pieces are brought nearer together and the area of the mouth reduced, the head resistance first decreases to a minimum and then increases. The lowest resistance found was about 50 per cent of that of the unstreamlined core, with a mouth area of one-half of the frontal area of the core. Air flow through the core was measured by pitot static tubes, one at the rear mouth of the casing and the other

at the front mouth (this latter tube was supported behind the casing, extending through the casing and core to the front mouth). The air flow obtained is represented in Table 19 by the values of k_s for the equation

$$M_s = k_s S$$

where M_s = air flow in pounds per second per square foot *of core*.
S = wind tunnel air speed, miles per hour.
(Air density = 0.0750 pounds per cubic foot.)

TABLE 19.—Air Flow in Stream-Lined Radiator

Mouth opening	k_s (front tube)	k_s (rear tube)
9-inch	0.062	0.063
6-inch	.043	.046
3-inch		.021
Not stream lined (12-inch section)	k_s=0.063	

By means of the head resistance, the weight and the heat transfer corresponding to the air flow, figure of merit was computed for each width of mouth and is shown in Fig. 44. In order to show the effect of weight, it has been computed for casings of galvanized iron and of aluminum. The curves show that at low speeds the increase in weight and decrease in air flow are so great as to be detrimental to the general performance. But at high speeds weight is of much less importance in comparison with head resistance, and the net effect of the casing seems to be a gain in performance. An easy method of shuttering could be provided by making the stream-line sides of the casing adjustable for different widths of mouth.

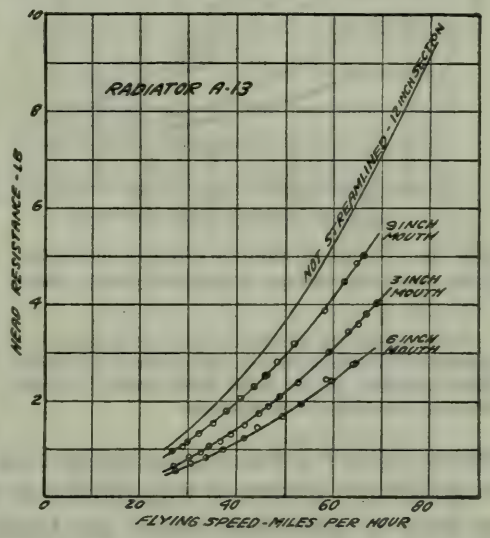


FIG. 43.—*Head resistance of stream-line casing inclosing radiator core*

The core section was 12 inches square, and a casing of the form shown in Fig. 42, with 6-inch mouth, reduces the head resistance of the combination by one-half. Neither the smaller mouth area (3 inch) or larger mouth area (9 inch) is nearly so effective in this respect

C. METHODS OF MEASURING GEOMETRICAL CHARACTERISTICS

The following characteristics of the core were measured:

(*a*) Dimensions of the water tubes: Length (in the direction of water flow), depth (parallel to the direction of air flow), thickness (perpendicular to length and depth), and hydraulic radius (quotient of cross section by perimeter).

(*b*) Dimensions of air tubes: Depth (parallel to air flow) and hydraulic radius.

(*c*) Free area of air passages.

(*d*) Extent and distribution of cooling surface.

(*e*) Weight of core, empty and filled with water.

(*f*) Nature and thickness of metal.

(*g*) Shape of air and water passages.

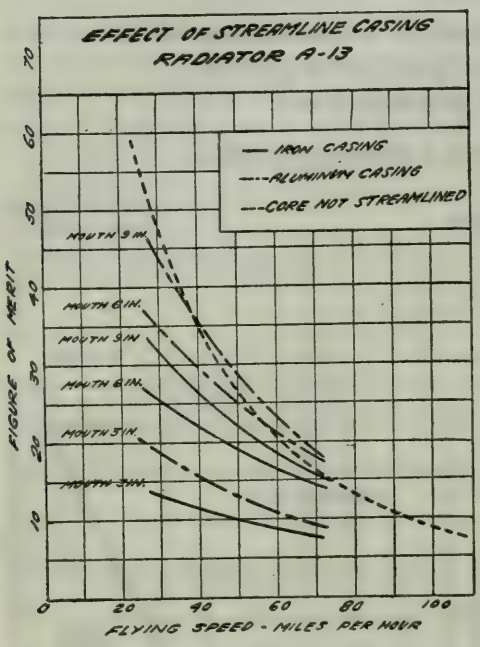


FIG. 44.—*Figure of merit of radiator core inclosed in stream-line casings of different shapes, shown in Fig. 42*

At low speeds, the increased weight and decreased heat dissipation fail of being offset by the advantage of decreased head resistance. At the higher flying speeds, it appears that such design may be advantageous

85. MEASURING DIMENSIONS OF THE WATER TUBES.—The apparatus used to measure the cross section of the water tubes is shown in Fig. 45. A radiator section *R*, with water tubes *t*–*t*, was placed upright on a support and water from a graduated burette *B* was allowed to flow into it until it reached a level h_2 somewhat above the lower ends of the water tubes. This level h_2 was read on the gage *G* and the position of the water surface on the burette scale was also read. More water was admitted and readings taken at from 6 to 10 levels up to one such, as h_1, near the upper ends of the water tubes. The burette was then lowered to the position (1), and similar readings were taken while emptying the radiator. The burette was calibrated by weighing its contents at various levels, and the gage was calibrated by comparison with a dividing engine. Readings were taken to 1 cm^3 in the burette and to 0.01 cm in the gage.

Volumes in cm^3 were plotted against heights in cm, and since all of the water that flows out of the burette passes into the radiator and the gage the slope of the resulting line (in cm^3 per cm) is the area of cross section of the water tubes and the gage. The area of the gage was determined by noting the heights occupied by known volumes of water. Two or more tests were made on each section, both while filling and while emptying it.

The number of tubes was counted and their depth measured with a rule and calipers. In cases where the tubes were not vertical, as in hexagonal cell types, the horizontal area computed as explained above was projected on a plane normal to the direction of water flow. From the total cross sectional area of the water tubes, their number, and their depth, the thickness and hydraulic radius were computed.

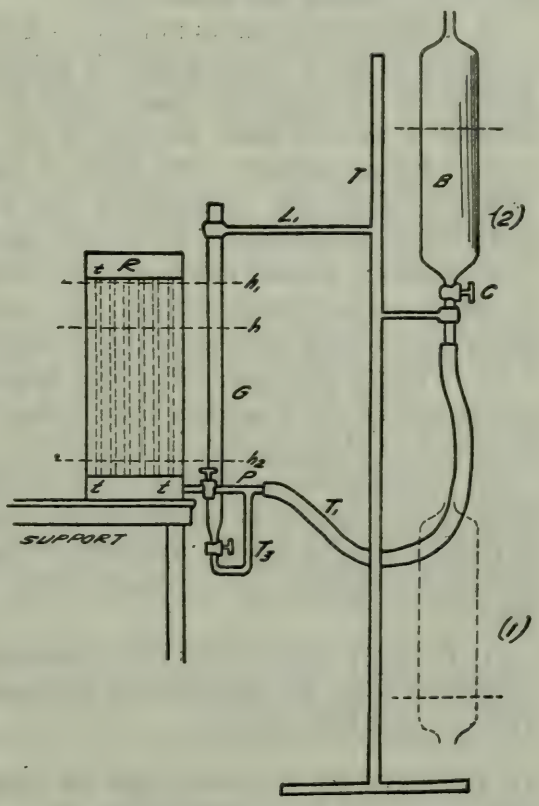


FIG. 45.—*Apparatus for measuring cross sectional area of water tubes in a radiator*

The principle is to measure by a burette (*B*) the volume of water filling a selected length of a radiator tube cluster, measured on the gage *G*

86. MEASURING DIMENSIONS OF THE AIR TUBES.—The method of measuring the air passages was similar to that used for the water tubes. The section was clamped face down on the top rim of a shallow tank about 18 cm (7 inches) square, provided with two openings to which rubber tubes were attached, leading to the burette and the gage. The rim of the tank was 2.5 cm (1 inch) wide and faced with a strip of soft rubber, so that the edges of the section could be sealed water-tight. The perimeter of the air tubes was determined from micrometer measurements on the

inside of the tubes, which also furnished a check on the measurement of their area. Depth of the air tubes is identical with that of the core and was measured with a rule and calipers.

87. Computing Free Area.—The free area of the air passages is the ratio of the area of the air passages to the frontal area of the core, due attention being given to the number of tubes filled with water during the measurement.

88. Computing Cooling Surface.—Cooling surface, in the case of simple types of construction, is evidently the product of the number of air tubes by their perimeter and by their length. Inspection showed what fraction of the surface was direct and what fraction indirect. The ends of the tubes were rated as indirect. When the construction was irregular, many different methods of measurement were used, depending upon the form. Two observers worked independently, and every effort was made to obtain values reliable within 2 per cent, but in few cases they could not be fixed with certainty to better than 10 per cent.

89. Weight of Core.—This was determined by weighing the empty core, without headers, on a balance. The computed water content was added to this for the weight when filled.

90. Composition of Metal.—No attempt was made to determine exact composition of the metal, which has been described as either copper or brass. Thickness of metal was measured with micrometer calipers and is reliable within about 0.001 inch (0.02 mm).

91. Form of Air and Water Passages.—Was determined by inspection aided by approximate measurements and is shown in Table 20 and Figs. 51–121.

VI. EFFECTS OF CONDITIONS OF USE ON PERFORMANCE

A. POSITION

This section, like the preceding chapter, is partly in the nature of a summary and will involve a certain amount of repetition of previous statements.

92. Unobstructed Positions.—Unobstructed positions have the following advantages:

(*a*) Except for effects of the slip stream the air flow through the core, and consequently the heat dissipation, are greater for unobstructed than for obstructed positions.

(*b*) Head resistance chargeable to the radiator is considerably less for unobstructed positions than for positions in the nose of the

fuselage, inside of the fuselage, and probably for positions in the wing. The effect of the slip stream is to increase the head resistance of a radiator that would otherwise be unobstructed.

(*c*) Since air flow is greater in unobstructed than in obstructed positions, and therefore heat dissipation per unit frontal area is greater, it follows that the weight of a radiator may be less for a given cooling capacity when in an unobstructed than when in an obstructed position.

(*d*) With reduction both in weight and in head resistance chargeable to the radiator, the power absorbed chargeable to the radiator is reduced by placing the radiator in an unobstructed position rather than in an obstructed position.

(*e*) With both increase in heat dissipation and decrease in power absorbed, the figure of merit of an unobstructed radiator is considerably greater than that of the same type of radiator in an obstructed position.

Some unobstructed positions have the disadvantages of requiring long connecting pipes and of being poorly adapted to shuttering the radiator. Methods of shuttering are discussed below.

93. Nose of the Fuselage.—The location of the radiator in the nose of the fuselage is objectionable because of very large absorption of power for a given cooling capacity. Not only is the resistance of the airplane much greater with a nose radiator than with the nose properly stream lined and an unobstructed radiator of equivalent cooling capacity added, but the air flow through the core is so low that with engines of the higher powers it becomes necessary to enlarge the fuselage to accommodate a nose radiator of size sufficient to cool the engine. Positions inside of the fuselage have been tried, but are open to the same objections as positions in the nose.

94. Wing Positions.—The performance of a radiator in the wing has not been thoroughly investigated because of experimental difficulties, but enough data are available to show that the air flow, and consequently the heat dissipation, are very low for a given flying speed, while the effect on the wing as such can only be detrimental, and the power absorbed chargeable to the radiator is probably large.

95. Slip-Stream Positions.—The effect of the propeller slip stream is to increase to some extent the air flow and heat dissipation of the radiator. No specific statement can yet be made in regard to its effects on the head resistance of radiators in obstructed positions.

96. YAWED POSITIONS.—The effect of yawing the radiator, or turning it so that the air strikes it at some other angle than parallel to the axis of the air tubes, is to decrease the air flow somewhat and to increase the head resistance. No experimental work has been done at this Bureau to determine the effect of yawing on heat dissipation, but both French and British reports state that a small increase has been found with certain angles and with certain types of core. The magnitude of the effect of yawing greatly varies with different types of radiator (see art. 39).

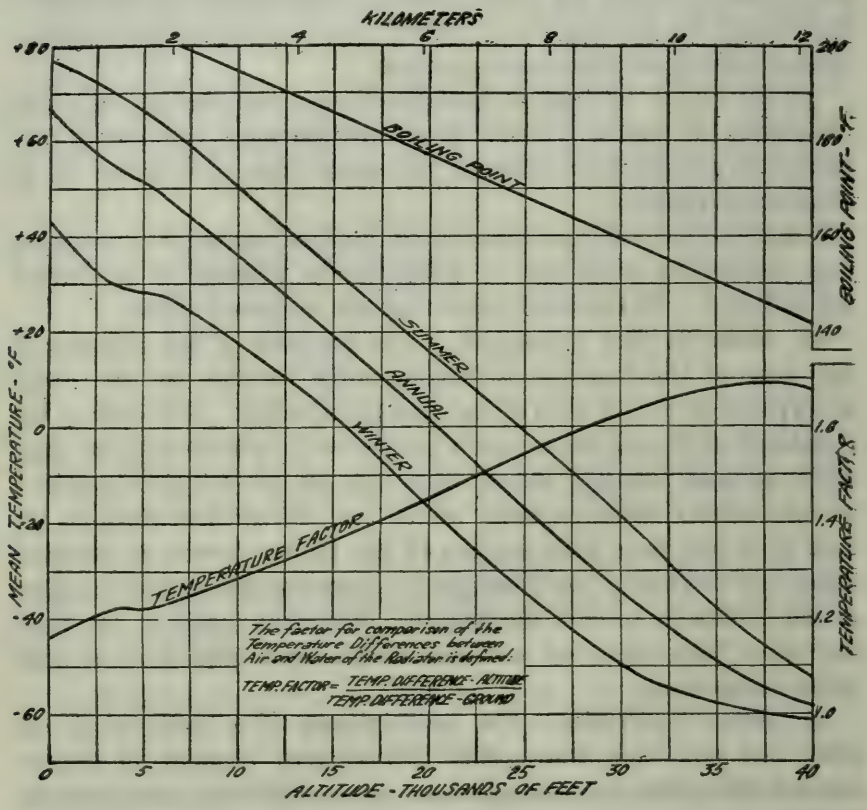


FIG. 46.—*Atmospheric conditions at altitude. Temperature (mean weather for United States)*

Boiling point is computed from mean pressure, the difference between summer and winter values not affecting boiling point appreciably for this application

B. EFFECTS OF ALTITUDE CONDITIONS ON PERFORMANCE

97. ATMOSPHERIC CONDITIONS AT ALTITUDES.—At high altitudes both the density and the temperature of the air are less than at the ground, and changes in these conditions have important effects upon the performance of the radiator. The decrease in air

temperature tends to increase the cooling capacity, while the decrease in density of the air tends to decrease both the cooling capacity and the absorption of power.

For a given flying speed both the air flow through the core and the head resistance are proportional to the density. Heat dissipation is practically proportional to the temperature difference between air and water, and for a given temperature difference and air flow (mass flow of air) is found to be independent of density (see art. 61).

Since atmospheric conditions are changing continually, it is evident that any estimate of performance at an altitude must be

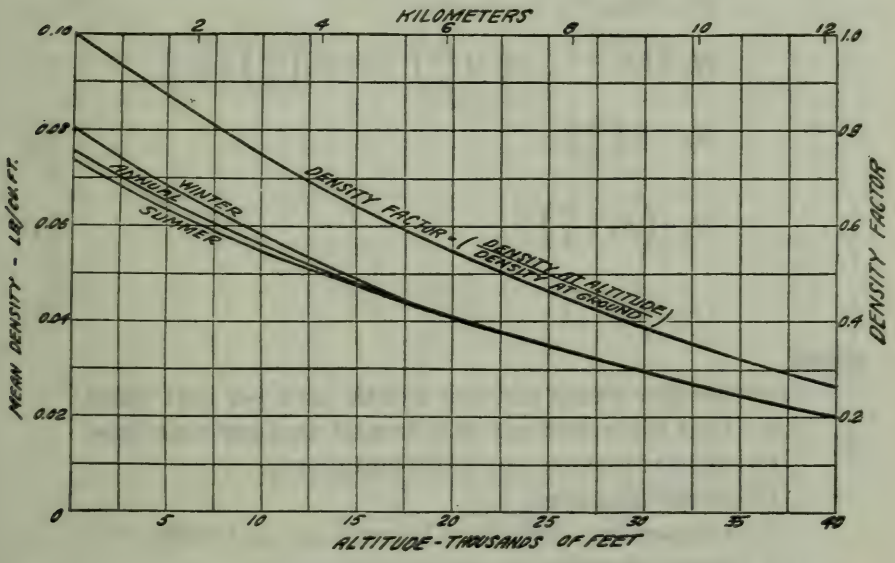


FIG. 47.—*Atmospheric conditions at altitude. Density (mean weather for United States)*

based upon assumed conditions, such as mean summer density and temperature, and also upon assumed requirements of operation, such as the maximum allowable water temperature. Probable atmospheric conditions at altitudes may be estimated from Figs. 46 and 47, which are drawn from data given by W. R. Gregg in the Monthly Weather Review, January, 1918, based upon observations at four stations situated in Indiana, Nebraska, South Dakota, and California. The boiling points shown correspond to mean annual pressure, only one line being plotted, because the difference between annual and summer or winter averages (1.5° F at 25,000 feet and less at lower altitudes) is so small that it may safely be neglected, in view of the uncertainties in all altitude conditions.

98. EQUATIONS OF PERFORMANCE.—If the performance of a radiator at the ground is known for a particular flying speed, its performance *at the same speed* at altitudes may be estimated by the following equations, using the subscripts a and o to denote values at altitudes and at the ground, respectively, and noting that density and temperature difference "at the ground" are to be taken as the density and temperature difference to which tests at the ground are reduced:

$$M_a = M_o\left(\frac{\rho_a}{\rho_o}\right) \tag{1}$$

$$H_o = bM_o^n T_o \tag{2}$$

$$H_a = bM_a^n T_a = b\left(M_o\frac{\rho_a}{\rho_o}\right)^n T_a = H_o\left(\frac{\rho_a}{\rho_o}\right)^n\left(\frac{T_a}{T_o}\right) \tag{3}$$

$$R_a = R_o\left(\frac{\rho_a}{\rho_o}\right) \tag{4}$$

$$P_a = \left(R_a + \frac{w}{r}\right)\frac{S}{c} \tag{5}$$

$$F = \frac{H_a}{P_a} \tag{6}$$

where

M = air flow (mass per unit frontal area per unit time),
H = heat dissipated per unit frontal area per unit time,
R = head resistance per unit frontal area,
P = power absorbed,
T = temperature difference between air and water,
F = figure of merit,
ρ = air density,
w = weight of core and contained water,
r = lift-drift ratio,
S = flying speed,
c = a conversion factor (0.00267 for the English units),
b, n = constants of the radiator.

In the equations above it will be noted that the performance of a radiator at any altitude in terms of its performance under standard test conditions at ground level at the same flying speed is computed by using two factors, ρ_a/ρ_o, a density factor, and T_a/T_o, a temperature factor. These factors, computed for each altitude are shown in Figs. 46 and 47. Since the atmosphere grows colder as altitude increases, the temperature difference

between the air and a given water temperature for the radiator becomes greater and the temperature factor increases. The factor does not start with unity at ground level, because average weather conditions impose a temperature difference somewhat greater than the standard test difference of 100° F (55.6° C).

99. Effects of Altitude Conditions on Properties.—Fig. 47, showing the ratio of density at altitudes to density at the ground, also represents the variation of both air flow and head

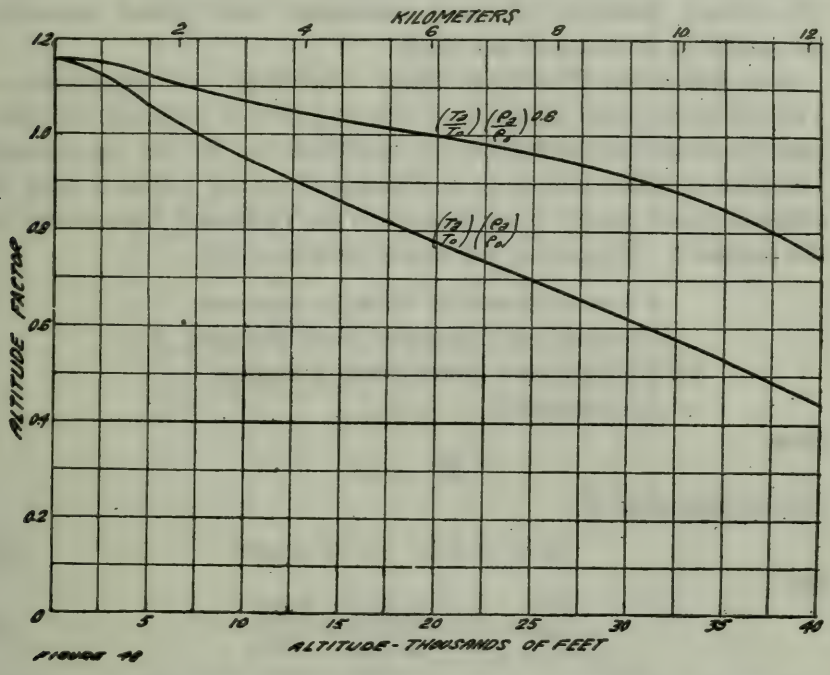


Fig. 48.—*Heat dissipation factor for altitude*

The heat dissipation of the radiator under conditions prevailing at altitude is computed from the heat dissipation under normal test conditions of air density 0.075 lbs. per ft.^{3} and temperature difference 100° F between entrance air and average water temperatures, by multiplying by the factor plotted above. Factors are plotted for two very different types of radiator, $n=1.00$ and 0.60, respectively, in the empirical equation $H=bM^nT$

resistance with altitude for a given flying speed. (The curves are nearly identical for summer, winter, and annual means, and only that based on the annual mean is plotted.)

The variation of heat dissipation with altitude at a given flying speed depends by equation (3) both upon the exponent n of the empirical equation applying to the radiator and upon the maximum allowable temperature of the water. The curves of Fig. 48 are computed on the assumption of mean annual conditions of the atmosphere and the requirement that the mean temperature of

the water in the radiator shall be 30° F below the boiling point,[27] and for such types of core that the exponent n takes the values 1.00 and 0.60.

The effect of altitude on figure of merit at given flying speeds is shown in Fig. 49 for three typical radiators, computed from the above equations and the properties of the radiators at the ground. These values are for unobstructed positions and a lift-drift ratio of 5.4. The above equations apply, however, to obstructed and slip-stream positions if head resistance and power absorbed *chargeable to the radiator* are used.

100. Relative Frontal Area Required at Altitudes.—The relative frontal area of radiator required at different altitudes may be estimated as follows for positions not in the slip stream. The rate at which heat is to be dissipated by the radiator may be assumed to be nearly proportional to the indicated horsepower of the engine.[28] Extending the above notation, let

A = frontal area of radiator required,
H' = total heat transfer from the area A,
IHP = indicated horsepower of engine,
a', b = constants.

Now

$$M = a'\rho S$$

and by equation (2)

$$H' = bATM^n = bAT(a'\rho S)^n \qquad (7)$$

and

$$\frac{H'_a}{H'_o} = \frac{A_a T_a (\rho_a S_a)^n}{A_o T_o (\rho_o S_o)^n} = \frac{IHP_a}{IHP_o}. \qquad (8)$$

Therefore, the ratio of the area required at an altitude to that required at the ground is given by

$$\frac{A_a}{A_o} = \frac{IHP_a}{IHP_o}\left(\frac{T_o}{T_a}\right)\left(\frac{\rho_o}{\rho_a}\right)^n\left(\frac{S_o}{S_a}\right)^n \qquad (9)$$

The factors $\frac{T_a}{T_o}$ and $\frac{\rho_a}{\rho_o}$ may be read from Figs. 46 and 47, while the factors $\frac{S_o}{S_a}$ and $\frac{IHP_a}{IHP_o}$ are obtained from the performance of the engine and plane.

[27] This assumption is entirely arbitrary. It may be noted, also, that it determines the starting point of the temperature factor curve of Fig. 46, giving 182° F as the water temperature; mean weather temperature is +67° F, a difference of 115° F as against 100° F standard test temperature difference.

[28] Unless affected by such abnormal conditions as heat leak from the turbine of a supercharger or of the exhaust manifold to the cylinder jackets.

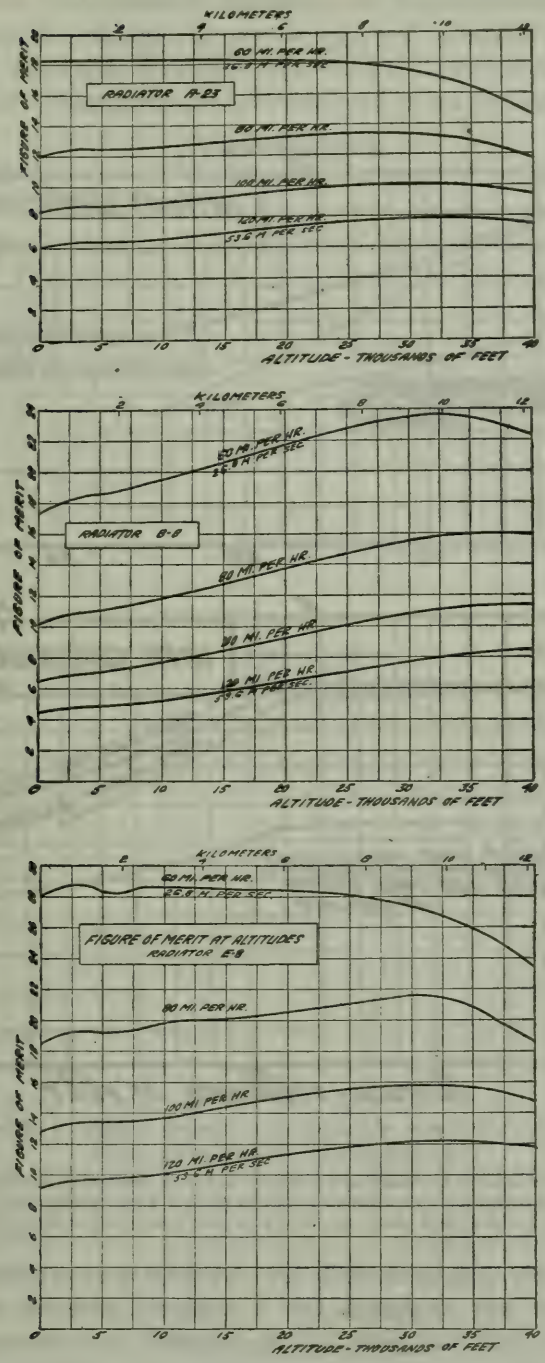


FIG. 49.—*Figures of merit for typical radiators at altitude, computed from mean annual weather data for the United States and from test data under ground conditions*

The curves correspond to the arbitrary specification that at each altitude the radiator size is so chosen as to maintain the mean temperature of the water in the radiator at 30° F below the boiling point

As an illustration of the method of computing radiator area required at altitude, Fig. 50 shows the results of computations based on data submitted to the National Advisory Committee for Aeronautics[29] for a Le Pere biplane equipped with variable-

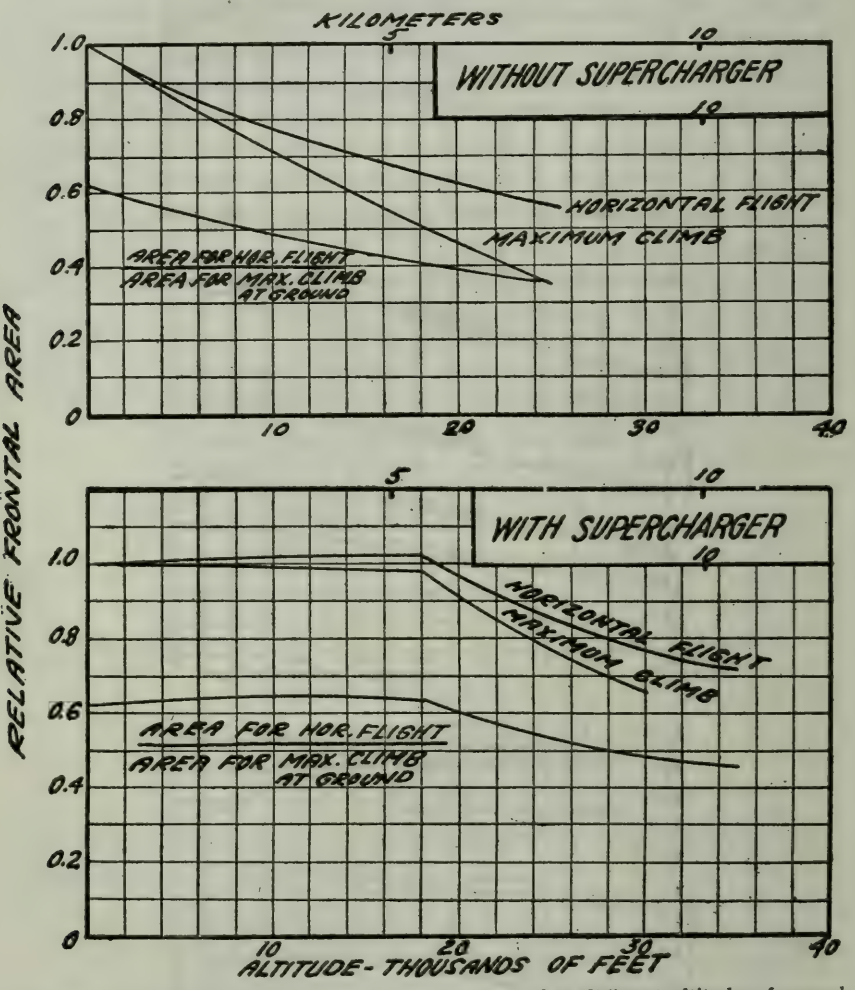


FIG. 50.—*Relative frontal area of radiator core required at different altitudes, for unobstructed position not in the slip stream*

Computations are based on the data shown in Figs 46 and 47 for atmospheric conditions at altitude. The airplane characteristics assumed include a lift drift ratio of 5.4, a variable pitch propeller controlled so as to hold engine speed always at 1800 r. p. m., and a supercharger designed for critical altitude of 5.5 kilometers (18 000 ft.)

pitch propeller and both with and without a supercharger. The supercharger was designed for a critical altitude of 5500 m (18 000 feet), and the pitch of the propeller was assumed so controlled that the speed of the engine was maintained constant at 1800 r. p. m.

[29] Report yet to be prepared for publication.

C. METHODS OF SHUTTERING

101. DETACHABLE SECTIONS.—Change of radiator capacity by the use of detachable sections is good for seasonal corrections such as summer and winter conditions, and for change from one latitude to another.

102. RETRACTABLE TYPES.—Retractable types will allow withdrawing the radiator or a part of it into the fuselage when its full cooling capacity is not needed. This is one of the best methods from the standpoint of heat dissipation and head resistance, for only the part of the radiator really required for use need be outside of the fuselage where it will affect the resistance of the plane. Difficulties may be encountered, however, in designing the fuselage for such an installation.

103. SIDE RADIATORS.—Two radiators may be used, one on each side of the fuselage, fitted with shutters that may be two plates for each radiator, hinged at the sides of the fuselage and swinging out to mask the front and rear faces to any desired extent. This method gives approximately the advantages of an unobstructed position, except for the slip stream, and avoids some of the difficulties in design encountered with the retractable type.

104. WINDOW-BLIND SHUTTERS.—Shutters of the window-blind type are objectionable because they add greatly to the resistance of the radiator when closed, and their effect in increasing head resistance and decreasing air flow is by no means negligible when open.[30]

105. PIVOTED TYPES.—Some attempts have been made to use a radiator pivoted about a vertical axis, so that it can be swung into or out of the air stream. This method is unsatisfactory, because when the radiator is turned about a vertical axis or yawed the heat dissipation may even be increased rather than diminished, while the head resistance will in general be increased. The method not only fails to give satisfactory control of cooling capacity, but adds considerably to the absorption of power.

106. REGULATION OF WATER FLOW.—Control by regulation of the water flow has been suggested, but no satisfactory method has been proposed. If the water is cut off from a part of the radiator, that part is likely to freeze at great altitudes or in cold weather, while a change in the rate of flow is not practicable, because with the rates commonly used in practice the heat dissipated is almost independent of the rate of flow.

[30] Since for a radiator in the nose of the fuselage, a decrease in air flow is accompanied by a decrease in head resistance chargeable to the radiator; shuttering a nose radiator decreases the resistance of the entire plane.

107. STREAM-LINE CASING.—If a stream-line casing for the radiator should be found useful, it would seem to be a simple problem to stream line the core in one dimension and the headers in the other, to arrange the stream line sides to open or close, and to put the mechanism for controlling them inside of the stream-line casing of the headers.

VII. GENERAL TABLES AND PLOTS

108. GEOMETRICAL CHARACTERISTICS OF RADIATOR.—In the following tables and plots the geometrical characteristics and physical properties of the radiator cores measured are collected for reference. There are a number of specimens on which for various reasons complete measurements were not made, and these have been separated from the others in the tables.

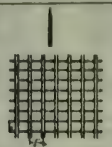
Table 20 shows geometrical characteristics and Table 21 shows physical properties, and a series of graphs show the performance of the different types of radiators. All performance figures as given apply to unobstructed positions, but the relation between heat dissipation and air flow is independent of the position.

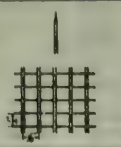
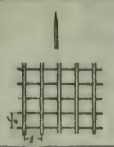
CLASSIFICATION OF CORES

The laboratory classification of the cores was accidental rather than logical, but the general underlying subdivision is as follows, a good many exceptions occurring which can only be identified by the headings of Table 20 or by Figs 51–121:

A=Square cell
B=hexagonal
C=circular
D=miscellaneous
E=flat plate
F=fin and tube
G=miscellaneous.

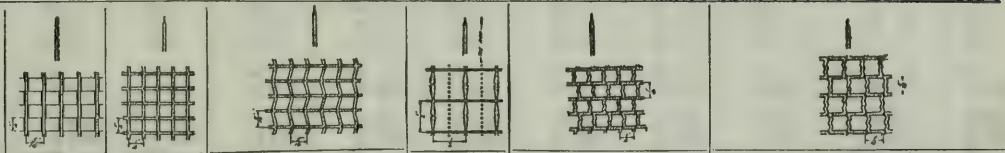
TABLE 20.—Geometrical Characteristics of Cores



Type	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-13
Metal:										
Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass
Fins				Copper						
Per cent free area	65.5	65.7	79.6	76.5	68.0	74.9	64.2	66.2	66.8	70.4
Cooling surface per unit frontal area	39.3	51.9	30.3	28.6	36.6	49.1	62.6	30.3	37.3	43.9
Per cent direct cooling surface	44.0	44.0	46.6	44.1	47.3	46.6	52.2	47.8	47.7	50.3
METRIC UNITS:										
Depth, cm	7.5	9.9	6.1	7.3	7.6	10.0	12.3	6.0	7.2	8.5
Thickness of metal, mm	0.13	0.13	0.13	0.15	0.10	0.10	0.13	0.13	0.13	0.13
Water tubes:										
Length, in cm/cm of core	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Width, mm	1.14	1.20	.99	1.48	1.55	1.37	1.98	1.63	1.68	1.32
Depth, cm	6.02	8.00	5.28	6.99	6.95	9.15	11.30	5.23	6.32	7.61
Spacing, mm	6.35	6.35	7.26	10.17	7.26	7.63	6.35	6.78	6.78	6.49
Area normal to flow, cm^2/cm	1.04	1.51	.72	1.02	1.50	1.65	3.52	1.26	1.56	1.55
Hydraulic radius, mm	0.536	0.584	0.482	0.726	0.787	0.685	0.965	0.792	0.812	0.648
Air tubes:										
Hydraulic radius, mm	1.27	1.27	1.60	1.98	1.42	1.55	1.27	1.32	1.32	1.40
Ratio, length ÷ hyd. radius	59	78	38	37	53	65	97	45	55	61
Weight, kg/m^2 front:										
Empty	67.1	89.1	47.0	56.9	50.2	67.7	83.4	40.1	49.0	55.4
Water content	10.4	15.1	7.2	10.2	14.9	16.5	35.3	12.7	15.5	15.4
Filled	77.5	104.2	54.2	67.1	65.1	84.2	118.7	52.8	64.5	70.8
ENGLISH UNITS:										
Depth, inches	2.9	3.9	2.4	2.9	3.0	4.0	4.9	2.4	2.8	3.4
Thickness of metal, inches	0.005	0.005	0.005	0.006	0.004	0.004	0.005	0.005	0.005	0.005
Water tubes:										
Length, in./ft. of core	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Width, inches	0.045	0.047	0.039	0.058	0.061	0.054	0.078	0.064	0.066	0.052
Depth, inches	2.4	3.1	2.1	2.7	2.7	3.6	4.4	2.1	2.5	3.0
Number per foot	48	48	42	30	42	40	48	45	45	47
Area normal to flow $ft.^2/ft.$	0.0340	0.0495	0.0237	0.0333	0.0491	0.0541	0.1156	0.0414	0.0510	0.0507
Hydraulic radius, inches	0.021	0.023	0.019	0.029	0.031	0.027	0.038	0.031	0.032	0.025
Air tubes:										
Hydraulic radius, inches	0.050	0.050	0.063	0.078	0.056	0.061	0.050	0.052	0.052	0.055
Ratio, length ÷ hyd. radius	59	78	38	37	53	65	97	45	55	61
Weight, $lbs./ft.^2$ front:										
Empty	13.8	18.3	9.6	11.6	10.3	13.9	17.1	8.2	10.0	11.3
Water content	2.1	3.1	1.5	2.1	3.1	3.4	7.0	2.6	3.2	3.2
Filled	15.9	21.4	11.1	13.7	13.4	17.3	24.1	10.8	13.2	14.5
Figure number	51	52	53	54	55	56	57	58	59	60

TABLE 20.—Geometrical Characteristics of Cores—Continued



		Type	A-14	A-15	A-16	A-17	A-18	A-19	A-20	A-21	A-22	A-23
		Metal:										
		Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass
		Fins	Copper									
		Per cent free area	72.1	53.0	69.8	72.1	83.0	67.7	66.9	65.6	66.6	68.5
		Cooling surface per unit frontal area	46.3	35.3	34.6	47.1	27.6	40.3	66.8	31.5	42.5	54.5
		Per cent direct cooling surface	48.6	42.7	43.9	43.5	46.7	86.9	92.1	86.0	91.1	91.8
METRIC UNITS		Depth, cm	9.9	7.5	7.6	10.2	10.2	7.6	12.7	7.5	10.1	12.7
		Thickness of metal, mm	0.15	0.13	0.15	0.13	0.13	0.13	0.13		0.13	0.13
		Water tubes:										
		Length, cm/cm of core	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00
		Width, mm	1.37	1.38	1.30	1.22	2.26	.72	.71	1.04	.90	1.02
		Depth, cm	9.65	6.60	6.80	9.22	9.26	6.70	11.75	6.58	9.31	11.78
		Spacing, mm	8.25	6.23	7.63	7.63	14.51	6.35	6.35	7.82	8.04	7.82
		Area normal to flow, cm^2/cm	1.72	1.47	1.15	1.46	1.40	.76	1.33	.87	1.06	1.54
		Hydraulic radius, mm	0.724	0.924	0.632	0.610	1.067	0.356	0.356	0.505	0.452	0.505
		Air tubes:										
		Hydraulic radius, mm	1.55	1.19	1.57	1.57		1.30	1.27	1.60	1.60	1.62
		Ratio, length÷hyd. radius	64	63	49	65		59	100	47	63	78
		Weight, kg/m^2 front:										
		Empty	89.0	59.1	59.0	77.4	43.5	67.3	112.0	45.4	61.0	76.0
		Water content	17.2	14.7	11.5	14.6	14.0	15.2	26.5	17.3	21.2	30.
		Filled	106.2	73.8	70.5	92.0	57.5	82.5	138.5	62.7	82.2	106.5
ENGLISH UNITS		Depth, inches	3.9	3.0	3.0	4.0	4.0	3.0	5.0	3.0	4.0	5.0
		Thickness of metal, inches	0.006	0.005	0.006	0.005	0.005	0.005	0.005		0.005	0.005
		Water tubes:										
		Length, in./ft. of core	12.0	12.0	12.0	12.0	12.0	24.0	24.0	24.0	24.0	24.0
		Width, inches	0.054	0.054	0.051	0.048	0.089	0.028	0.028	0.041	0.035	0.040
		Depth, inches	3.8	2.6	2.7	3.6	3.6	2.6	4.6	2.6	3.7	4.6
		Number per foot	37	49	40	40	21	48	48	39	38	39
		Area normal to flow, $ft.^2/ft$	0.0565	0.0482	0.0378	0.0480	0.0459	0.0249	0.0435	0.0284	0.0348	0.0505
		Hydraulic radius, inches	0.028	0.036	0.025	0.024	0.042	0.014	0.014	0.020	0.018	0.020
		Air tubes:										
		Hydraulic radius, inches	0.061	0.047	0.062	0.062		0.051	0.050	0.063	0.063	0.064
		Ratio, length÷hyd. radius	64	63	49	65		59	100	47	63	78
		Weight, $lbs./ft.^2$ front:										
		Empty	18.2	12.1	12.1	15.8	8.9	13.8	22.9	9.3	12.5	15.5
		Water content	3.5	3.0	2.4	3.0	2.9	3.1	5.4	3.5	4.3	6.3
		Filled	21.7	15.1	14.5	18.8	11.8	16.9	28.3	12.8	16.8	21.8
		Figure number	61	62	63	64	65	66	67	68	69	70

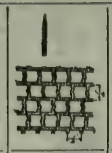
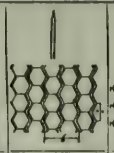
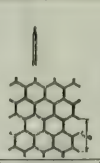
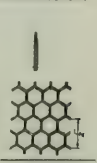
										
Type	A–25	A–33	A–34	B–1	B–2	B–3	B–4	B–5	B–6	B–7
Metal:										
Water tubes	Copper	Brass	Brass	Brass	Copper	Brass	Brass	Brass	Brass	Copper
Fins										
Per cent free area	67.1	63.4	66.4	83.6	88.0	79.6	72.7	81.2	79.0	77.0
Cooling surface per unit frontal area	53.2	49.6	63.6	21.6	36.1	26.8	37.2	23.8	37.9	45.8
Per cent direct cooling surface	90	52.6	49.2	37.5	34.6	58.6	28.0	27.8	26.7	27.7
METRIC UNITS: Depth, cm	10.2	9.8	12.3	6.4	10.2	7.7	8.3	5.2	8.3	10.2
Thickness of metal, mm	0.13	0.13	0.13	0.15	0.15	0.13	0.13	0.10	0.13	0.13
Water tubes:										
Length, cm/cm of core	2.00	1.00	1.00	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Width, mm	.66	1.60	1.70	1.42	.48	1.09	1.30	1.33	1.45	1.57
Depth, cm	9.15	9.15	10.95	5.61	9.60	6.80	7.31	4.40	6.81	8.64
Spacing, mm	6.35	6.50	6.80	17.96	16.97	10.16	10.51	13.87	13.87	13.87
Area normal to flow, cm^2/cm	.96	2.24	2.85	.45	.27	.84	.90	.42	.71	.96
Hydraulic radius, mm	0.330	0.813	0.864	0.685	0.231	0.623	0.635	0.660	0.711	0.756
Air tubes:										
Hydraulic radius, mm	1.30	1.30	1.32	2.23	2.26	2.26	1.35	1.80	1.78	1.76
Ratio, length ÷ hyd. radius	79	77	93	34	45	.....	62	29	47	57
Weight, kg/m^2 front:										
Empty	90.0	66.0	78.5	32.7	52.4	45.5	60.1	26.8	42.9	52.5
Water content	19.0	22.5	28.5	5.2	3.1	9.7	10.4	4.9	8.2	11.0
Filled	109.0	88.5	107.0	37.9	55.5	55.2	70.5	31.7	51.1	63.5
ENGLISH UNITS: Depth, inches	4.0	3.8	4.8	2.5	4.0	3.0	3.3	2.0	3.3	4.0
Thickness of metal, inches	0.005	0.005	0.005	0.006	0.006	0.005	0.005	0.004	0.005	0.005
Water tubes:										
Length, in./ft. of core	24.0	12.0	12.0	13.9	13.9	13.9	13.9	13.9	13.9	13.9
Width, inches	0.026	0.063	0.067	0.056	0.019	0.043	0.051	0.052	0.057	0.062
Depth, inches	3.6	3.6	4.3	2.2	3.8	2.7	2.9	1.7	2.7	3.4
Number per foot	48	47	45	17	18	30	29	22	22	22
Area normal to flow, $ft.^2/ft$	0.0314	0.0736	0.0934	0.0148	0.0087	0.0276	0.0295	0.0139	0.0232	0.0315
Hydraulic radius, inches	0.013	0.032	0.034	0.027	0.009	0.024	0.025	0.026	0.028	0.030
Air tubes:										
Hydraulic radius, inches	0.051	0.050	0.052	0.088	0.089	0.090	0.053	0.071	0.070	0.070
Ratio, length ÷ hyd. radius	79	77	93	34	45	.....	62	29	47	57
Weight, lbs./$ft.^2$ front:										
Empty	18.4	13.5	16.1	6.7	10.7	9.3	12.3	5.5	8.8	10.7
Water content	3.9	4.6	5.8	1.1	.6	2.0	2.1	1.0	1.7	2.2
Filled	22.3	18.1	21.9	7.8	11.3	11.3	14.4	6.5	10.5	12.9
Figure number	.....	.....	.....	71	72	73	74	75	76	77

TABLE 20.—Geometrical Characteristics of Cores—Continued

	Type	B–8	B–9	B–10	B–11	B–12	B–13	B–14	B–15	B–16	B–17
	Metal: Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Copper
	Fins										
	Per cent free area	73. 3	65. 1	65. 1	65. 1	65. 1	65. 1	65. 9	65. 2	64. 1	65. 2
	Cooling surface per unit frontal area	56. 1	36. 2	25. 5	30. 4	34. 0	41. 6	27. 7	36. 3	36. 4	40. 2
	Per cent direct cooling surface	30. 3	66. 5	62. 7	64. 8	66. 2	67. 6	89. 2	89. 6	90. 7	92. 6
METRIC UNITS	Depth, cm	13. 4	8. 9	6. 4	7. 6	8. 3	10. 2	7. 6	10. 1	10. 1	9. 5
	Thickness of metal, mm	0. 13	0. 10	0. 13	0. 13	0. 10	0. 13	0. 13	0. 13	0. 13	0. 22
	Water tubes:										
	Length, cm/cm of core	1. 15	1. 23	1. 23	1. 23	1. 23	1. 23	2. 00	2. 00	2. 00	2. 00
	Width, mm	2. 09	2. 00	2. 00	2. 08	1. 83	2. 00	1. 19	1. 32	1. 27	. 76
	Depth, cm	12. 30	7. 77	5. 15	6. 35	7. 26	9. 05	6. 94	9. 17	9. 33	8. 89
	Spacing, mm	14. 51	9. 83	8. 48	8. 48	8. 48	8. 48	8. 97	8. 97	8. 98	7. 82
	Area normal to flow, cm^2/cm	1. 77	1. 59	1. 23	1. 56	1. 56	2. 15	0. 89	1. 31	1. 25	. 85
	Hydraulic radius, mm	1. 016	0. 980	0. 965	1. 006	0. 890	1. 016	0. 585	0. 635	0. 610	0. 381
	Air tubes:										
	Hydraulic radius, mm	1. 75	1. 63	1. 63	1. 63	1. 63	1. 63	1. 85	1. 83	1. 83	1. 55
	Ratio, length ÷ hyd. radius	76	54	39	47	52	63	41	55	55	61
	Weight, kg/m^2 front:										
	Empty	68. 2	50. 8	36. 0	43. 4	46. 9	58. 0	44. 8	57. 9	57. 9	87. 9
	Water content	20. 4	19. 7	15. 1	19. 2	19. 3	26. 4	17. 7	25. 4	25. 0	17. 1
	Filled	88. 6	70. 5	51. 1	62. 6	66. 2	84. 4	62. 5	83. 3	82. 9	105. 0
ENGLISH UNITS	Depth, inches	5. 3	3. 5	2. 5	3. 0	3. 3	4. 0	3. 0	4. 0	4. 0	3. 7
	Thickness of metal, inches	0. 005	0. 004	0. 005	0. 005	0. 004	0. 005	0. 005	0. 005	0. 005	0. 0085
	Water tubes:										
	Length, in./ft. of core	13. 9	14. 8	14. 8	14. 8	14. 8	14. 8	24. 0	24. 0	24. 0	24. 0
	Width, inches	0. 082	0. 079	0. 079	0. 082	0. 072	0. 079	0. 047	0. 052	0. 050	0. 030
	Depth, inches	4. 8	3. 1	2. 0	2. 5	2. 9	3. 6	2. 7	3. 6	3. 7	3. 5
	Number per foot	21	31	36	36	36	36	34	34	34	39
	Area normal to flow, $ft.^2/ft.$	0. 0579	0. 0521	0. 0402	0. 0511	0. 0512	0. 0705	0. 0290	0. 0430	0. 0410	0. 028
	Hydraulic radius, inches	0. 040	0. 039	0. 038	0. 040	0. 035	0. 040	0. 023	0. 025	0. 024	0. 015
	Air tubes:										
	Hydraulic radius, inches	0. 069	0. 064	0. 064	0. 064	0. 064	0. 064	0. 073	0. 072	0. 072	0. 061
	Ratio, length ÷ hyd. radius	76	54	39	47	52	63	41	55	55	61
	Weight, lbs./$ft.^2$ front:										
	Empty	14. 0	10. 4	7. 4	8. 9	9. 6	11. 9	9. 2	11. 8	11. 8	18. 0
	Water content	4. 2	4. 0	3. 1	3. 9	3. 9	5. 4	3. 6	5. 2	5. 1	3. 5
	Filled	18. 2	14. 4	10. 5	12. 8	13. 5	17. 3	12. 8	17. 0	16. 9	21. 5
	Figure number	78	79	80	81	82	83	84	85	86	87

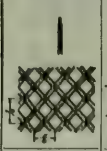
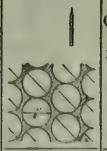
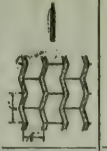
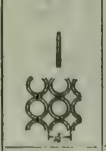
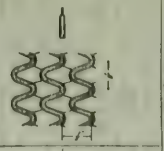
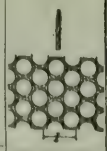
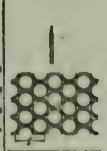
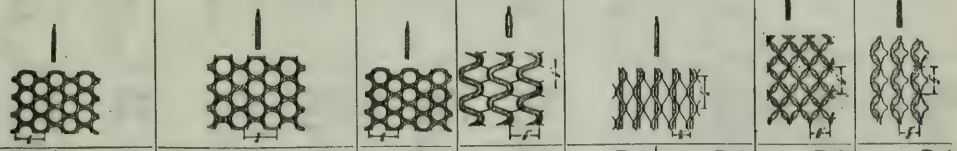
				Construction identical with C-2a except that vanes in air tubes run back only about one-fourth the depth of the core.						
Type		C-1	C-2	C-2a	C-2b	C-4	C-5	C-6	C-7	C-8	C-9
Metal:											
Water tubes		Brass	Brass	Brass	Brass	Brass	Copper	Copper	Copper	Copper	Copper
Fins											
Per cent free area		51.9	60.4	63.2	62.5	62.6	49.5	70.9	70.8	60.0	61.1
Cooling surface per unit frontal area		32.1	48.3	76.6	56.7	32.0		30.4	32.5	34.7	33.8
Per cent direct cooling surface		94.2	87.2	56.3	75.9	57.2		46.4	46.4	94.0	93.0
METRIC UNITS	Depth cm	8.6	21.2	21.1	21.2	7.4	8.7	7.6	8.9	12.8	10.2
	Thickness of metal mm	0.13	0.10		0.13	0.13	0.13	0.15	0.15		
	Water tubes:										
	Length, cm/cm of core	1.24	1.15	1.15	1.15	1.15	1.43	1.32	1.40	1.87	1.87
	Width mm	1.80	3.00	2.82	3.00	1.85	1.52	1.73	2.24	1.52	1.40
	Depth cm	8.08	18.86	18.80	18.96	6.35	8.69	6.40	7.77	11.91	9.37
	Spacing mm	5.35	12.20	11.72	11.72	7.10	5.55	11.30	12.20	11.50	8.97
	Area normal to flow cm^2/cm	2.72	4.91	4.51	4.80	1.67	2.41	.97	1.43	1.82	1.48
	Hydraulic radius mm	0.876	1.579	1.398	1.575	0.901	0.762	0.838	1.085	0.844	0.694
	Air tubes:										
	Hydraulic radius mm	1.40	2.72			1.58		1.88	1.90	2.26	1.88
	Ratio, length÷hyd. radius	62	78			47		41	47	57	54
	Weight, kg/m^2 front:										
	Empty	47.0	76.7	93.8	81.6	45.0	89.6	44.4	51.5	61.0	53.7
	Water content	32.1	56.5	52.1	37.2	19.2	34.5	17.7	19.9	34.0	27.6
	Filled	79.1	133.2	145.9	118.8	64.2	124.1	62.1	71.4	95.0	81.3
ENGLISH UNITS	Depth inches	3.4	8.3	8.3	8.4	2.9	3.4	3.0	3.5	5.0	4.0
	Thickness of metal inches	0.005	0.004		0.005	0.005	0.005	0.006	0.006		
	Water tubes:										
	Length, in./ft. of core	14.9	13.9	13.9	13.9	13.8	17.2	15.8	16.7	22.4	22.4
	Width inches	0.071	0.118	0.111	0.118	0.073	0.060	0.068	0.088	0.060	0.052
	Depth inches	3.2	7.4	7.4	7.5	2.5	3.4	2.5	3.1	4.7	3.7
	Number per foot	57	25	26	26	43	55	27	25	29	34
	Area normal to flow, $ft.^2/ft$	0.089	0.161	0.148	0.1575	0.055	0.079	0.032	0.047	0.063	0.048
	Hydraulic radius inches	0.034	0.062	0.055	0.062	0.035	0.030	0.033	0.043	0.033	0.027
	Air tubes:										
	Hydraulic radius inches	0.055	0.107			0.062		0.074	0.075	0.089	0.074
	Ratio, length÷hyd. radius	62	78			47		41	47	57	54
	Weight, lbs./$ft.^2$ front:										
	Empty	9.6	15.7	19.2	16.7	9.2	18.3	9.1	10.5	12.5	11.0
	Water content	6.6	11.6	10.7	7.6	3.9	7.1	3.6	4.1	6.9	5.6
	Filled	16.2	27.3	29.9	24.3	13.1	25.4	12.7	14.6	19.4	16.6
Figure number		88	89	90		91	92	93	94	95	96

TABLE 20.—Geometrical Characteristics of Cores—Continued



		C-10	C-11	C-12	C-13	C-14	C-17	D-1	D-2	D-3	D-4
	Type										
	Metal:										
	Water tubes	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Brass	Brass	Brass
	Fins										
	Per cent free area	57.9	60.6	59.8	65.3	64.3	66.7	75.8	68.7	45.5	65.8
	Cooling surface per unit frontal area	32.2	32.6	66.6	57.8	71.4	32.5	23.7	84.1	32.6	42.0
	Per cent direct cooling surface	92.0	92.7	96.7	95.9	96.4		46.8	44.9	83.1	42.1
METRIC UNITS	Depth, cm	10.2	10.2	25.3	20.2	20.2	8.8	6.8	20.3	8.9	8.9
	Thickness of metal, mm		0.17	0.14	0.15		0.13	0.13	0.13	0.10	0.13
	Water tubes:										
	Length, cm/cm of core	1.87	1.87	1.87	1.87	1.87	1.39	1.00	1.00	1.23	1.23
	Width, mm	1.32	1.47	1.93	1.50	1.19	2.52	1.88	2.35	1.78	2.22
	Depth, cm	9.37	9.60	24.68	19.50	19.61	7.60	5.59	10.04	7.36	7.36
	Spacing, mm	8.97	9.25	9.25	10.16	8.97	12.70	10.51	12.70	5.26	10.51
	Area normal to flow, cm^2/cm	1.55	1.64	4.74	3.07	3.00	1.50	1.06	3.52	2.53	1.55
	Hydraulic radius, mm	0.746	0.788	0.896	0.842	0.670	0.122	0.965	1.165		
	Air tubes:										
	Hydraulic radius, mm	1.85	1.90	2.28	2.28	1.83	1.91				
	Ratio, length÷hyd. radius	55	53	111	88	111	46				
	Weight, kg/m^2 front:										
	Empty	53.7	53.6	93.2	74.2	82.0	51.5	41.4	131.2	62.3	44.6
	Water content	29.0	30.3	89.2	57.6	56.1	20.9	10.6	35.2	30.6	19.1
	Filled	82.7	83.9	182.4	131.8	138.1	72.4	52.0	166.4	92.9	63.7
ENGLISH UNITS	Depth, inches	4.0	4.0	10.0	8.0	8.0	3.5	2.7	8.0	3.5	3.5
	Thickness of metal, inches		0.007	0.0057	0.006		0.005	0.005	0.005	0.004	0.005
	Water tubes:										
	Length, in./ft. of core	22.4	22.4	22.4	22.4	22.4	16.7	12.0	12.0	14.7	14.7
	Width, inches	0.055	0.058	0.076	0.059	0.047	0.099	0.074	0.092	0.070	0.087
	Depth, inches	3.7	3.8	9.7	7.7	7.7	3.0	2.8	7.5	2 9	2.9
	Number per foot	34	33	33	30	34	24	29	24	58	29
	Area normal to flow, $ft.^2/ft.$	0.051	0.054	0.156	0.101	0.098	0.049	0.035	0.115	0.083	0.051
	Hydraulic radius, inches	0.029	0.031	0.035	0.033	0.026	0.048	0.038	0.046		
	Air tubes:										
	Hydraulic radius, inches	0.073	0.075	0.090	0.090	0.072	0.075				
	Ratio, length÷hyd. radius	55	53	111	88	111	46				
	Weight, $lbs./ft.^2$ front:										
	Empty	11.0	11.0	19.1	15.2	16.8	10.5	8.5	26.9	12.8	9.1
	Water content	5.9	6.2	18.3	11.8	11.5	4.3	2.2	7.2	6.3	3.9
	Filled	16.9	17.2	37.4	27.0	28.3	14.8	10.7	34.1	19.1	13.0
	Figure number	97	98	99	100	101		120	104	105	106

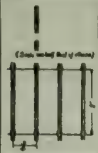
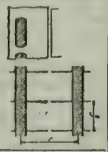
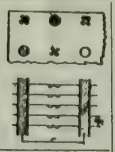
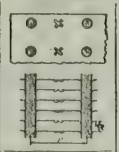
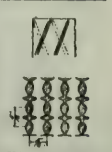
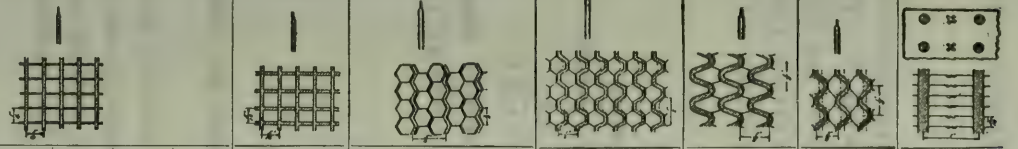
										
	E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8	E-9	E-10
Type										
Metal:										
Water tubes	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper
Fins										
Per cent free area	72.2	71.5	71.4	72.0	88.0	75.0	83.3	87.5	85.0	63.6
Cooling surface per unit frontal area	25.0	37.2	49.6	29.5	25.5	78.5	52.3	39.2	68.9	58.0
Per cent direct cooling surface	89.6	93.0	94.8	94.6	97.3	100.0	100.0	100.0	89.5	60.8
METRIC UNITS										
Depth, cm	12.2	18.6	24.8	24.1	23.7	24.8	24.8	24.7	59.1	14.6
Thickness of metal, mm	0.10	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.48	
Water tubes:										
Length, cm/cm of core	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Width, mm	1.85	1.85	1.85	1.85	1.85	1.33	1.33	1.33	1.57	
Depth, cm	5.74	5.74	5.74	5.74	5.96	24.80	24.80	24.70	4.72	
Spacing, mm	7.95	7.95	7.95	12.7	15.9	6.35	9.53	12.70	1.78	9.54
Area normal to flow, cm^2/cm	2.51	3.86	5.31	5.31	5.31	5.18	3.45	2.78	4.16	2.23
Hydraulic radius, mm	0.940	0.940	0.940	0.940		0.274	0.274	0.274	0.360	0.544
Air tubes:										
Hydraulic radius, mm						2.38	3.96	5.54		
Ratio, length÷hyd. radius						104	62	45		
Weight, kg/m^2 front:										
Empty	66.5	99.8	133.0	79.8	69.1	82.0	54.7	44.9	190.6	74.2
Water content	25.6	38.5	53.4	31.2	27.8	45.4	31.8	24.5	47.9	22.4
Filled	92.1	138.3	186.4	111.0	96.9	127.4	86.5	69.4	238.5	96.6
ENGLISH UNITS										
Depth, inches	4.8	7.3	9.8	9.5	9.3	9.8	9.8	9.7	23.2	5.7
Thickness of metal, inches	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.019	
Water tubes:										
Length, in./ft. of core	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Width, inches	0.073	0.073	0.073	0.073	0.073	0.052	0.052	0.052	0.062	
Depth, inches	2.3	2.2	2.3	2.3	2.3	9.7	9.8	9.7	1.9	
Number per foot	76	114	152	100	80	48	32	24	176	32
Area normal to flow, $ft.^2/ft.$	0.0824	0.1264	0.1740	0.174	0.1740	0.170	0.113	0.091	0.136	0.073
Hydraulic radius, inches	0.037	0.037	0.037	0.037		0.011	0.011	0.011	0.014	0.021
Air tubes:										
Hydraulic radius, inches						0.094	0.156	0.218		
Ratio, length÷hyd. radius						104	62	45		
Weight, $lbs./ft.^2$ front:										
Empty	13.6	20.4	27.2	16.3	14.2	16.8	11.2	9.2	39.0	15.2
Water content	5.2	7.9	10.9	6.4	5.7	9.3	6.5	5.0	9.8	4.6
Filled	18.8	28.3	38.1	22.7	19.9	26.1	17.7	14.2	48.8	19.8
Figure number				108		109	110	111	112	114

TABLE 20.—Geometrical Characteristics of Cores—Continued

									
Type	F–1	F–2	F–3	F–4	F–5	G–1	G–2	G–3	G–4
Water tubes	Copper	Copper	Brass	Copper	Brass	Brass	Copper	Copper	Copper
Fins			Copper		Copper				
Per cent free area	76.5	74.4					74.4	72.0	41.2
Cooling surface per unit frontal area	15.9	24.9	49.7	43.0	40.2	27.2	22.4	44.7	52.2
Per cent direct cooling surface	37.9	23.8	14.6	18.2	12.3	23.2	43.2	42.9	84.9
METRIC UNITS: Depth, cm	7.0	7.1	10.5	9.2	8.9	6.1	4.3	8.6	10.2
Thickness of metal, mm	0.15	0.15	0.10	0.10	0.13	0.13	0.15	0.13	0.13
Water tubes:									
Length, cm/cm of core	1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.09	1.00
Width, mm			6.00	8.60	5.97		1.84	1.75	3.23
Depth, cm			.60	.86	.60	4.67	3.30	3.30	8.45
Spacing, mm	21.8	21.8			17.0	10.51	8.97	8.97	8.04
Area normal to flow, cm^2/cm	.83	.76	.72	1.39	.66		.68	1.29	3.40
Hydraulic radius, mm	1.728	1.728	1.499	2.160	1.500		0.864	0.838	1.550
Air tubes:									
Hydraulic radius, mm									
Ratio, length ÷ hydraulic radius									
Weight, kg/m^2 front:									
Empty					43.2	42.4	26.8	53.6	63.3
Water content	8.3	7.6	7.2	13.9	6.3	6.8	7.4	14.4	34.0
Filled					49.5	49.2	34.2	68.0	97.3
ENGLISH UNITS: Depth, inches	2.8	2.8	4.1	3.6	3.5	2.4	1.7	3.4	4
Thickness of metal, inches	0.006	0.006	0.004	0.004	0.005	0.005	0.006	0.005	0.005
Water tubes:									
Length, in./ft. of core	12.0	12.0	12.0	12.0	12.0	12.0	13.1	13.1	12.0
Width, inches			0.235	0.340	0.235		0.072	0.069	0.127
Depth, inches			0.2	0.3	0.2	1.8	1.3	1.3	3.3
Number per foot	42	42	90	72	84	29	34	68	38
Area normal to flow, $ft.^2/ft.$	0.0273	0.0249	0.0237	0.0455	0.0216		0.022	0.042	0.111
Hydraulic radius, inches	0.068	0.068	0.059	0.085	0.059		0.034	0.033	0.061
Air tubes:									
Hydraulic radius, inches									
Ratio, length ÷ hydraulic radius									
Weight, lbs./$ft.^2$ front:									
Empty					8.8	8.7	5.5	11.0	13.0
Water content	1.7	1.5	1.5	2.8	1.3	1.4	1.5	2.9	7.0
Filled					10.1	10.1	7.0	13.9	20.0
Figure number					115	116	117	119	120



Type	A-26	A-27	A-28	A-29	A-30	A-31	A-32	B-18	B-19	B-20	B-21	C-15	C-16	F-6
Metric units:														
Depth....cm	11.0	8.5	12.3	11.0	8.5	5.9	7.6	8.9	8.9	10.2	7.6	8.9	7.7	7.9
Weight, empty....kg/m²	75.6	58.0	65.4	61.8	46.0	39.6	61.3	52.8	45.5	57.4	43.4	51.5	48.6	37.0
English units:														
Depth....inches	4.3	3.3	4.8	4.3	3.3	2.3	3.0	3.5	3.5	4.0	3.0	3.5	3.0	3.1
Weight, empty....lb./ft.²	15.5	11.9	13.4	12.7	9.4	8.1	12.5	10.8	9.3	11.8	8.9	10.5	9.9	7.6

FLAT PLATE ASSEMBLIES

Radiator	A	B	C	D	E	F	G	H	I	J	K
Number of plates	25	17	13	30	30	25	17	30	30	17	25
Metric units:											
Depth....cm	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5	20.3	20.3	20.3
Pitch....cm	1.27	1.89	2.54	0.95	0.95	1.27	1.89	0.64	0.95	1.89	1.27
Thickness....cm	0.318	0.318	0.318	0.318	0.159	0.159	0.159	0.159	0.159	0.159	0.159
English units:											
Depth....inches	12	12	12	12	12	12	12	12	8	8	8
Pitch....inches	1/2	3/4	1	3/8	3/8	1/2	3/4	1/4	3/8	3/4	1/2
Thickness....inches	1/8	1/8	1/8	1/8	1/16	1/16	1/16	1/16	1/16	1/16	1/16

Radiator	L	M	N	O	P	Q	R	S	T	U	V
Number of plates	17	25	30	17	25	30	30	25	17	17	30
Metric units:											
Depth....cm	20.3	20.3	20.3	5.1	5.1	5.1	5.1	5.1	5.1	10.2	10.2
Pitch....cm	1.89	1.27	0.95	1.89	1.27	0.95	0.95	1.27	1.89	1.89	0.95
Thickness....cm	0.318	0.318	0.318	0.318	0.318	0.318	0.159	0.159	0.159	0.318	0.138
English units:											
Depth....inches	8	8	8	2	2	2	2	2	2	4	4
Pitch....inches	3/4	1/2	3/8	3/4	1/2	3/8	3/8	1/2	3/4	3/4	3/8
Thickness....inches	1/8	1/8	1/8	1/8	1/8	1/8	1/16	1/16	1/16	1/8	1/8

109. PHYSICAL PROPERTIES OF RADIATORS.—Empirical constants are for the equations

$M = k\,S$

$H = b\,M^n$

$R = c\,S^2$ { R is nearly proportional to S^2 or c is approximately constant, although varying slightly with S. The value tabulated corresponds to $S = 60$ miles per hour and may be used with fair accuracy (within 5 per cent) for speeds from 40 to 90 miles per hour,

where

M = air flow, $\frac{\text{lb.}}{\text{sec.} \times \text{sq. ft.}}$ or $\frac{\text{kg}}{\text{sec.} \times \text{m}^2}$

S = flying speed, miles per hour or meters per second,

R = head resistance, pounds per square foot or kg per m^2

H = heat dissipation, $\frac{\text{h. p.}}{\text{sq. ft. front} \times 100^\circ \text{ F}}$ or $\frac{\text{kw}}{\text{m}^2 \times 50^\circ \text{ C}}$

also q = surface heat dissipation coefficient for average linear speeds of 100 feet per second and 30 meters per second through the air tubes in

$$\frac{\text{h. p.}}{\text{sq. ft. surface} \times 100^\circ \text{ F}} \text{ or } \frac{\text{cal}}{\text{sec} \times \text{cm}^2 \times ^\circ \text{C}}$$

m = air flow constant,

F = figure of merit.

For k, c, and q, air density is assumed 0.0750 pounds per cubic foot, or 1.204 kg per m^3.

Most of the information in Table 21 is derived directly from measurements on each particular core, but for various reasons it was not convenient to make complete tests on every section, and the following quantities have been estimated by the methods noted:

Head resistance (by interpolation with respect to depth of core)		Air flow (by venturi meter)		Air flow (by equation (1) art. 20), using constants for similar types	Heat dissipation (by correction from old measurements taken before the "steam tunnel" had been put in the form described)
A-9	B-15	B-2	E-7		E-6
A-22	C-9	B-4	E-9	B-3	E-7
B-6	C-10	B-6	F-5	B-14	E-8
B-7	C-13	B-9	G-1	B-16	
B-9	E-6	C-2a	G-2		
B-11	E-7	C-2b	G-3		
B-12	E-8	C-6	G-4		

TABLE 21.—Physical Properties of Radiators

RADIATORS WITH COMPLETE DATA—ENGLISH UNITS

Radiator No.	m	k ×100	c ×1000	b	n	q (100 ft./sec.)	S=60 miles per hour			S=120 miles per hour		
							R	H	F	R	H	F
A-1	0.56	6.1	1.82	11.6	0.75	1.09	6.6	31.0	20.0	25.0	51	5.7
A-2	.43	4.7	1.81	11.8	.82	.97	6.5	28.0	16.6	25.0	49	5.2
A-3	.56	6.1	1.40	7.6	.70	.93	5.0	18.8	16.6	19.5	31	4.4
A-4	.62	6.8	1.48	8.0	.75	1.06	5.3	22.0	17.8	21.0	38	5.2
A-5	.54	5.9	1.76	9.9	.75	1.00	6.3	25.0	17.7	24.0	43	5.0
A-6	53	5.9	1.71	10.2	.80	.92	6.2	28.0	18.7	24.0	48	5.6
A-7	.47	5.1	1.86	15.1	.75	.93	6.7	35.0	19.6	26.0	59	6.0
A-8	.56	6.2	1.63	7.5	.80	.97	5.9	22.0	17.1	23.0	38	4.7
A-9	.56	6.1	1.67	9.8	.80	1.06	6.0	28.0	20.0	23.0	48	5.9
A-13	.57	6.3	1.46	8.4	.85	.88	5.2	26.0	20.0	20.0	47	6.4
A-14	.50	5.5	1.87	13.0	.70	1.03	6.7	29.0	17.0	26.0	48	5.0
A-15	.41	4.5	1.95	8.4	.90	.92	7.0	20.0	13.0	27.0	38	4.0
A-16	.57	6.3	1.34	7.5	.80	.88	4.8	22.0	18.1	18.7	38	5.6
A-17	.56	6.1	1.49	8.7	.85	.86	5.4	26.0	18.4	21.0	48	6.1
A-18	.66	7.2	1.14	6.6	.60	.74	4.1	16.0	15.9	15.9	24	4.1
A-19	.53	5.8	1.62	8.6	.85	.92	5.8	24.0	17.4	22.0	45	5.5
A-20	.44	4.8	1.90	13.1	.85	.91	6.8	32.0	16.6	26.0	58	5.7
A-21	.60	6.6	1.39	6.6	.85	.87	5.0	21.0	17.8	19.5	39	5.6
A-22	.54	5.9	1.46	8.7	.85	.88	5.3	25.0	19.0	20.0	46	6.2
A-23	.49	5.4	1.56	10.3	.85	.85	5.6	28.0	18.0	22.0	50	6.1
B-1	.68	7.5	1.14	6.4	.63	.97	4.1	16.4	18.5	15.8	26	4.6
B-2	.66	7.2	1.38	8.4	.60	.75	5.0	20.0	18.0	19.2	30	4.5
B-3	.64	6.9	1.35	5.9	.75	.88	4.9	17.4	15.7	18.8	28	4.2
B-4	.52	5.7	1.75	11.7	.65	1.05	6.3	26.0	18.4	20.4	41	4.7
B-5	.62	6.8	1.42	6.5	.60	.84	5.1	15.2	15.0	19.8	23	3.4
B-6	.62	6.8	1.60	9.5	.60	.78	5.8	22.0	18.0	22.0	34	4.3
B-7	.52	5.7	1.71	11.5	.60	.78	6.2	24.0	17.7	24.0	37	4.4
B-8	.44	4.8	1.91	13.1	.60	.69	6.9	25.0	15.0	27.0	38	3.9
B-9	.54	5.9	1.78	7.5	.85	.89	6.4	22.0	15.3	25.0	40	4.5
B-10	.60	6.6	1.61	6.4	.85	1.05	5.8	21.0	16.3	22.0	38	4.8

75013°—22——9

TABLE 21.—Physical Properties of Radiators—Continued

RADIATORS WITH COMPLETE DATA—ENGLISH UNITS—Continued

Radiator No.	m	k ×100	c ×1000	b	n	q (100 ft./sec.)	S=60 miles per hour			S=120 miles per hour		
							R	H	F	R	H	F
B-11	.57	6.3	1.69	8.0	.80	1.02	6.1	23.0	17.2	24.0	40	4.9
B-12	.58	6.4	1.74	8.6	.80	.99	6.2	25.0	17.9	24.0	43.	5.0
B-13	.51	5.6	1.87	8.9	.85	.92	6.7	24.0	15.2	26.0	45	4.8
B-14	.59	6.5	1.23	7.3	.72	.93	4.4	19.3	17.7	17.1	35	5.6
B-15	.54	6.0	1.44	8.0	.70	.91	5.2	23.0	17.0	20.0	42	5.6
B-16	.54	5.9	1.44	6.4	.53	.89	5.2	23.0	17.2	20.0	41	5.5
B-17	.60	6.6	1.47	8.2	.78	.94	5.3	28.0	19.1	21.0	52	6.4
C-1	.43	4.7	2.07	6.5	.68	.79	7.4	17.4	10.4	29.0	34	3.3
C-2	.45	4.9	1.70	8.7	.85	.72	6.1	22.0	12.2	24.0	39	4.4
C-2a	.43	4.7	1.85	13.0	.60	.49	6.7	24.0	12.5	26.0	37	3.7
C-4	.50	5.4	1.52	7.1	.85	.86	5.5	19.1	15.1	21.0	35	4.6
C-5	.30	3.3	1.89	9.0	.85	.75	6.8	15.4	8.4	26.0	29	2.9
C-6	.63	6.9	1.55	9.3	.70	1.06	5.6	25.0	20.0	22.0	41	5.3
C-7	.61	6.8	1.65	8.3	.80	1.07	6.0	25.0	18.3	23.0	44	5.4
C-8	.59	6.4	1.58	8.2	.85	.92	5.7	26.0	17.2	22.0	46	5.7
C-9	.57	6.2	1.65	8.0	.85	.92	6.0	24.0	16.3	23.0	44	5.3
C-10	.57	6.3	1.65	8.3	.85	.96	6.0	25.0	17.1	23.0	47.	5.6
C-11	.55	6.0	1.65	7.5	.73	1.00	6.0	24.0	16.4	23.0	45	5.3
C-12	.42	4.6	2.11	15.2	1.04	.89	7.6	33.0	14.0	29.0	58	5.0
C-13	.46	5.1	1.89	12.3	.96	.93	6.8	31.0	16.4	26.0	54	5.4
C-14	.38	4.2	2.06	13.0	1.10	1.02	7.4	32.0	15.9	29.0	60	5.5
D-1	.53	5.8	1.32	8.1	.70	1.25	4.8	19.1	17.7	18.5	32	4.8
D-2	.32	3.5	1.98	15.0	.70	.70	7.2	27.0	12.5	28.0	43	3.9
D-3	.42	4.6	2.31	8.7	.85	.83	8.3	20.0	10.6	33.0	37	3.2
D-4	.53	5.8	1.64	9.4	.70	.73	5.9	22.0	16.8	23.0	37	4.5
E-4	.40	4.4	1.84	10.	.85	1.55	6.7	23.0	13.3	.....	40	.....
E-6	.43	4.8	1.65	16.1	.80	1.00	5.9	37.0	21.0	23.0	65	7.3
E-7	.56	6.1	1.10	8.5	.90	.94	4.0	27.0	24.0	15.3	51	8.6
E-8	.58	6.3	.82	7.6	.80	.94	3.0	22.0	25.0	11.5	38	8.5
E-9	.37	4.1	1.8	9.1	1.00	.96	6.6	22.0	8.9	.....	45	.....
E-10	.30	3.3	2.38	.....	.....	1.43	8.6	32.0	16.4	35.0	58	4.7
G-1	.37	4.1	2.57	8.2	.60	.....	9.2	14.0	7.9	36.0	22	1.8
G-2	.52	5.7	2.08	9.4	.65	1.31	7.5	21.0	14.7	29.0	33	3.4
G-3	.38	4.2	2.40	14.8	.75	1.31	8.7	29.0	16.0	32.0	49	4.4
G-4	.....	.....	2.29	12.7	.70	.62	8.4	23.0	11.9	30.0	.....	.....

TABLE 21.—Physical Properties of Radiators—Continued

RADIATORS WITH INCOMPLETE DATA—ENGLISH UNITS

Radiator No.	m	k × 100	c × 1000	b	n	q (100 ft./sec.)
A-25	0.50	5.5	1.70			
A-26	.55	6.0	1.80			
A-27	.56	6.2	1.85			
A-28	.59	6.5	1.74			
A-29	.55	6.1	1.54			
A-30	.59	6.4	1.52			
A-31	.59	6.5	1.35			
A-32			1.45			
A-33	.54	6.0				
B-18			1.24			
B-19			1.13			
B-20			1.00			
B-21			1.86			
C-2b	.45	5.0		15.0	0.65	0.83
C-15			1.46			
C-16			2.43			
E-1						2.25
E-2	.36	3.9				1.85
E-3						1.80
E-5	.6	7.0				
F-1	.65	7.1				
F-2	.36	3.9				
F-5	.34	3.7				
F-6			2.68			

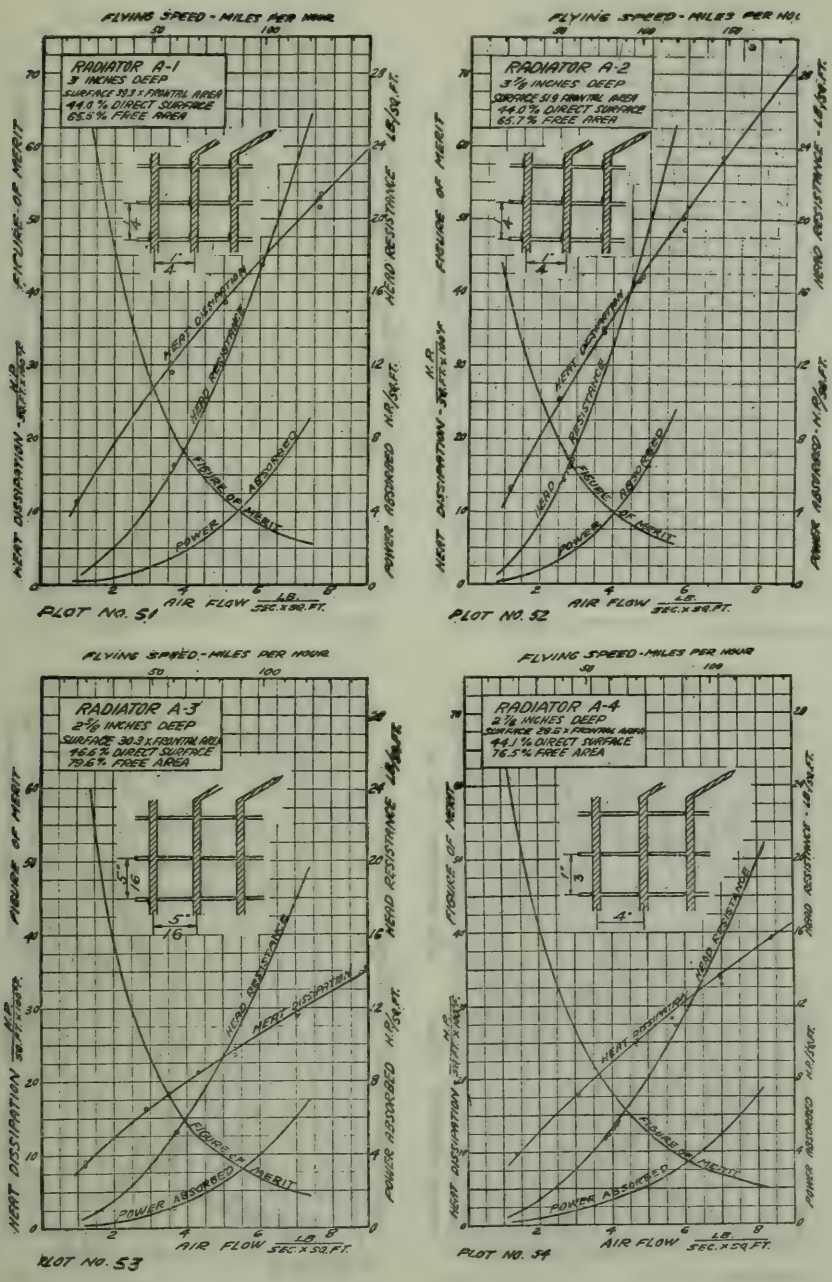
RADIATORS WITH INCOMPLETE DATA—METRIC UNITS

Radiator No.	m	k	c×100	q×1000 (30 m/sec)
A-25	0.50	0.60	4.2	
A-26	.55	.66	4.4	
A-27	.56	.67	4.5	
A-28	.59	.71	4.3	
A-29	.55	.66	3.8	
A-30	.59	.70	3.7	
A-31	.59	.71	3.3	
A-32			3.5	
A-33	.54	.65		
B-18			3.0	
B-19			2.8	
B-20			2.4	
B-21			4.5	
C-2b	.45	.55		2.83
C-15			3.6	
C-16			5.9	
E-1				7.82
E-2	.36	.43		6.34
E-3				6.14
E-5	.6	.7		
F-1	.65	.78		
F-2	.36	.43		
F-5	.34	.41		
F-6			6.6	

TABLE 21.—Physical Properties of Radiators—Continued

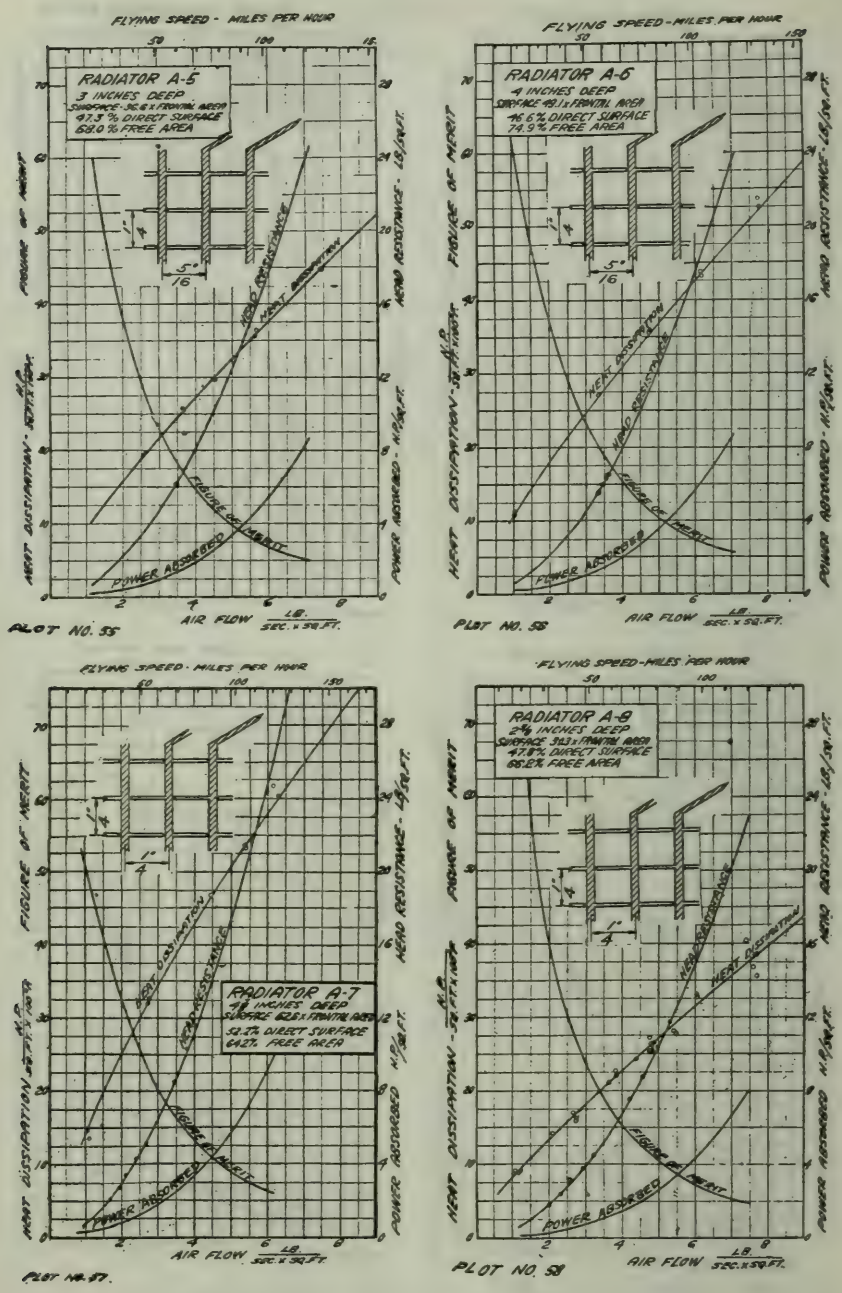
RADIATORS WITH COMPLETE DATA—METRIC UNITS

Radiator No.	m	k	c×100	q×1000 (30m/sec)	S=25 meters per sec			S=50 meters per sec		
					R	H	F	R	H	F
A–1	0.56	0.67	4.5	3.73	28.4	210	23.0	108.0	352	6.4
A–2	.43	.52	4.4	3.29	29.3	188	18.5	108.0	334	6.3
A–3	.56	.67	3.4	3.15	21.5	132	18.7	83.5	210	5.0
A–4	.62	.74	3.6	3.62	23.5	153	20.0	87.5	263	5.8
A–5	.54	.64	4.3	3.40	27.4	168	20.1	104.0	294	5.7
A–6	.53	.64	4.2	3.13	26.4	191	21.0	102.0	330	6.4
A–7	.47	.56	4.5	3.16	28.4	240	22.0	110.0	405	7.0
A–8	.56	.68	4.0	3.29	24.4	148	19.2	96.0	257	5.4
A–9	.56	.67	4.1	3.62	26.4	188	23.3	99.0	330	6.8
A–13	.57	.69	3.6	2.99	21.5	180	23.0	87.5	320	7.2
A–14	.50	.60	4.6	3.52	29.3	202	19.0	94.0	316	6.6
A–15	.41	.49	4.8	3.14	30.5	140	14.3	116.0	262	4.5
A–16	.57	.69	3.3	3.00	20.6	149	20.3	80.0	258	6.3
A–17	.56	.67	3.6	2.92	22.5	177	20.2	86.5	322	6.9
A–18	.66	.79	2.8	2.51	17.6	108	18.0	68.0	161	4.7
A–19	.53	.64	4.0	3.14	25.0	165	17.3	96.0	305	5.6
A–20	.44	.52	4.6	3.11	29.9	217	16.0	112.0	394	5.9
A–21	.60	.72	3.4	2.96	21.5	144	17.6	83.0	264	5.6
A–22	.54	.65	3.6	3.01	22.5	174	18.7	86.0	312	6.3
A–23	.49	.60	3.8	2.91	23.5	190	18.0	93.0	344	6.1
B–1	.68	.82	2.8	3.29	17.1	110	21.3	67.0	176	5.4
B–2	.66	.79	3.4	2.57	21.0	140	21.0	82.0	201	5.2
B–3	.64	.75	3.3	3.00	22.0	119	17.5	82.0	196	4.6
B–4	.52	.62	4.3	3.59	28.4	183	20.7	105.0	282	5.5
B–5	.62	.75	3.5	2.86	22.0	104	17.0	83.5	159	3.9
B–6	.62	.74	3.9	2.64	24.0	152	21.2	94.0	231	5.2
B–7	.52	.63	4.2	2.67	25.9	166	20.0	102.0	253	5.1
B–8	.44	.53	4.7	2.34	31.8	171	17.8	112.0	260	4.6
B–9	.54	.65	4.4	3.04	27.9	152	17.4	106.0	273	5.4
B–10	.60	.73	3.9	3.57	25.0	141	18.2	96.0	255	5.5
B–11	.57	.69	4.1	3.47	26.4	158	19.2	100.0	276	5.6
B–12	.58	.70	4.3	3.38	26.4	173	19.9	104.0	300	5.9
B–13	.51	.61	4.6	3.12	28.4	166	16.7	111.0	306	5.4
B–14	.59	.71	3.0	3.18	19.6	132	20.0	52.0	207	8.5
B–15	.54	.65	3.5	3.11	23.0	155	18.6	87.5	291	6.4
B–16	.54	.65	3.5	3.04	22.5	159	18.8	86.5	280	6.3
B–17	.60	.72	3.7	3.21	22.3	192	18.7	91.0	349	6.4
C–1	.43	.52	5.1	2.69	32.3	116	11.5	123.0	226	3.7
C–2	.45	.54	4.2	2.44	26.4	148	13.4	100.0	264	4.7
C–2a	.43	.51	4.5	1.67	29.8	169	13.7	111.0	257	4.5
C–4	.50	.60	3.7	2.95	23.5	128	16.8	91.0	235	5.1
C–5	.30	.36	4.6	2.56	30.3	110	8.7	121.0	199	3.2
C–6	.63	.76	3.8	3.63	24.4	174	22.9	90.0	278	6.4
C–7	.61	.74	4.0	3.66	25.9	177	20.3	99.0	304	5.9
C–8	.59	.71	3.9	3.14	23.5	170	18.8	93.0	315	6.4
C–9	.57	.68	4.0	3.12	25.4	157	18.2	98.0	301	5.9
C–10	.57	.69	4.0	3.27	25.4	166	18.9	98.0	316	6.4
C–11	.55	.66	4.0	3.42	25.0	163	18.4	99.0	303	6.0
C–12	.42	.51	5.2	3.04	32.3	221	15.2	125.0	401	5.1
C–13	.46	.55	4.6	3.18	29.8	210	17.7	113.0	350	6.1
C–14	.38	.45	5.0	3.49	32.8	220	17.0	121.0	406	6.2
D–1	.53	.63	3.2	4.25	20.6	130	19.8	66.9	206	5.5
D–2	.32	.39	4.8	2.37	29.3	192	14.1	120.0	302	4.5
D–3	.42	.50	5.6	2.84	37.2	136	11.8	141.0	248	3.6
D–4	.53	.64	4.0	2.49	25.0	151	19.0	96.0	252	5.2
E–4	.40	.48	4.5	5.30	28.8	156	14.6	.....	275	....
E–6	.43	.52	4.0	3.42	25.4	254	24.0	99.0	446	8.2
E–7	.56	.67	2.7	3.20	17.1	187	25.5	65.5	345	9.6
E–8	.58	.69	2.0	3.19	31.3	150	27.0	48.9	262	9.5
E–9	.37	.45	4.0	3.28	27.8	149	9.4	.....	300	....
E–10	.30	.36	5.8	4.88	36.2	220	18.3	142.0	396	5.5
G–1	.37	.45	6.3	.....	40.1	95	8.6	.....	147	2.1
G–2	.52	.63	5.1	4.46	32.8	145	16.9	125	228	3.8
G–3	.38	.45	5.9	4.45	36.2	200	18.0	138.0	336	4.9
G–4	.....	.....	5.6	2.11	37.1	160	13.0	129.0	273	4.1



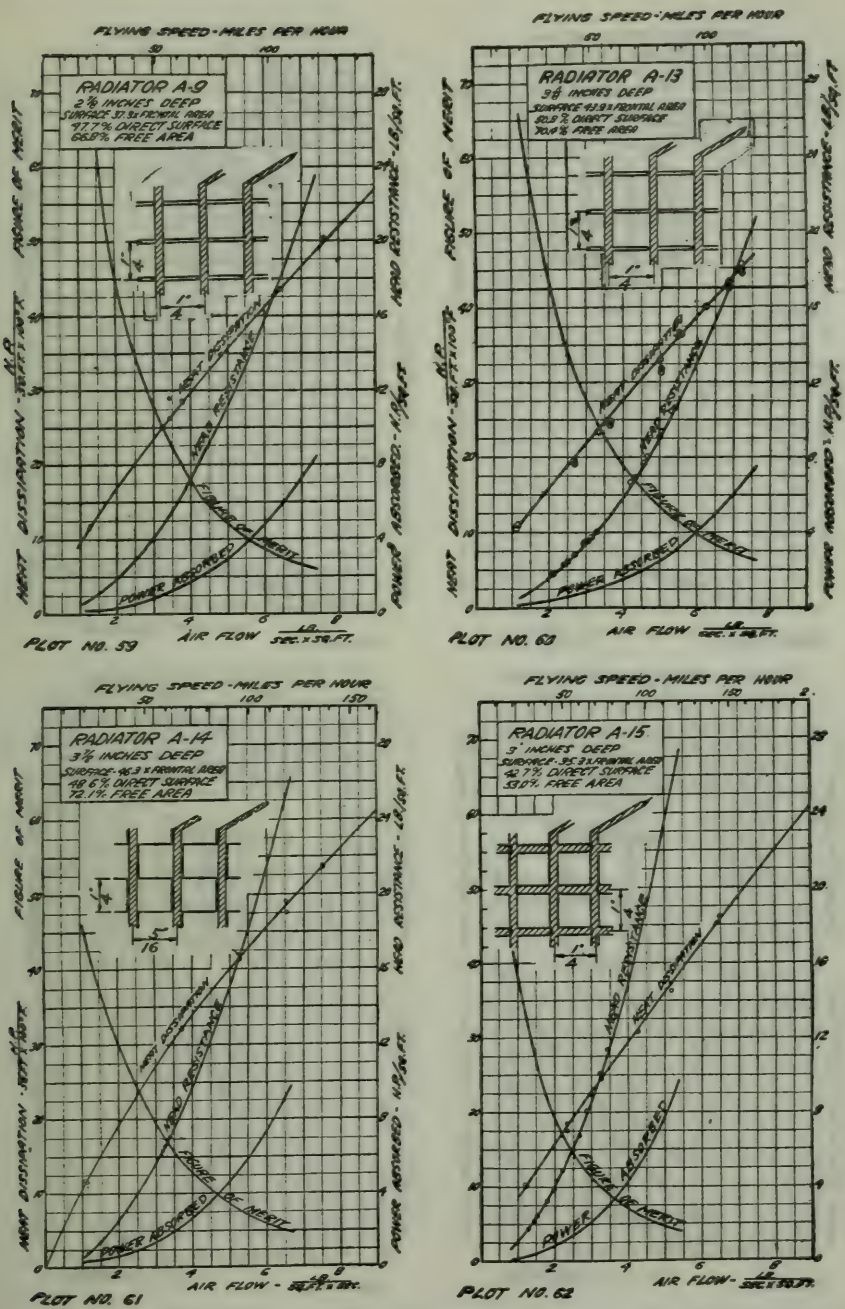
FIGS. 51–54.—*Performance curves of square cell radiator cores*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



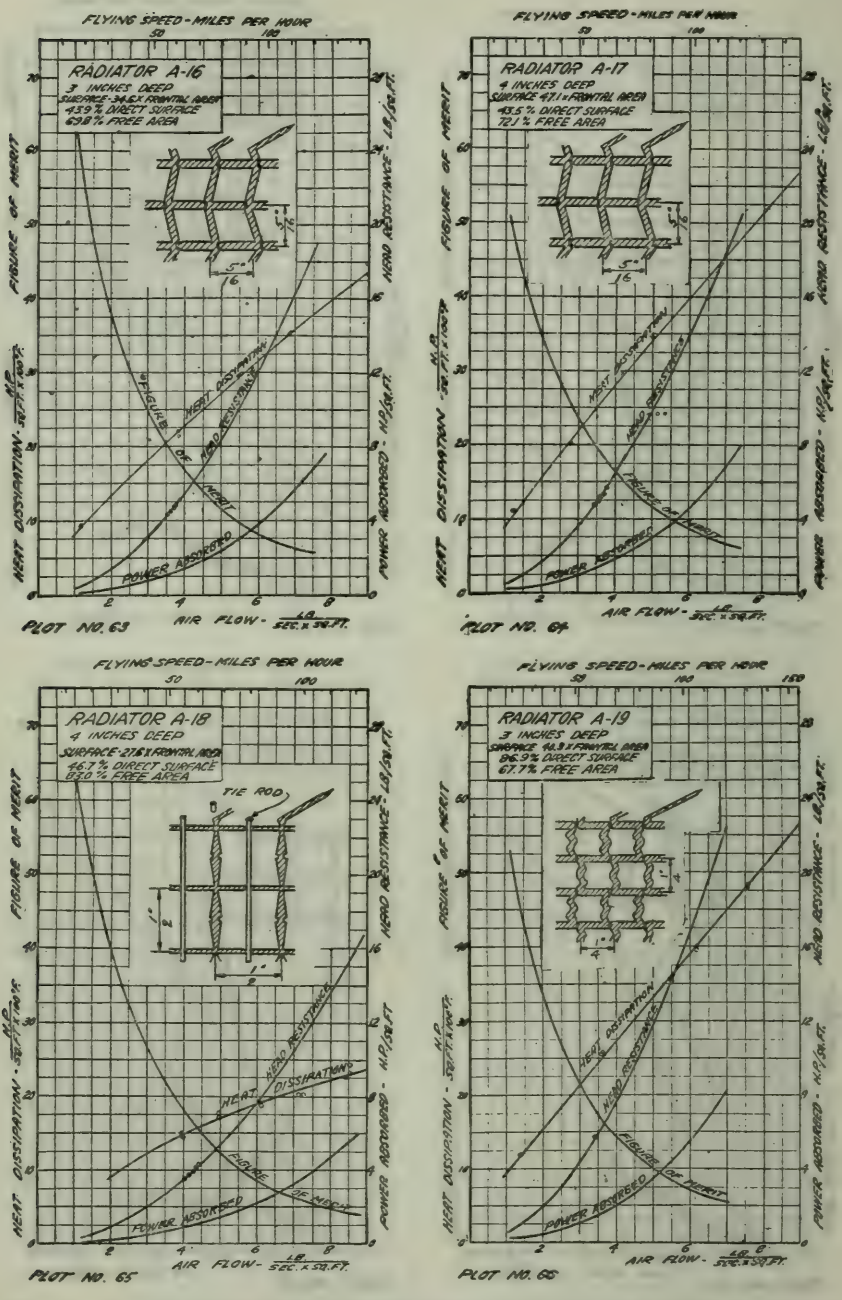
FIGS. 55–58.—*Performance curves of square cell radiator cores*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



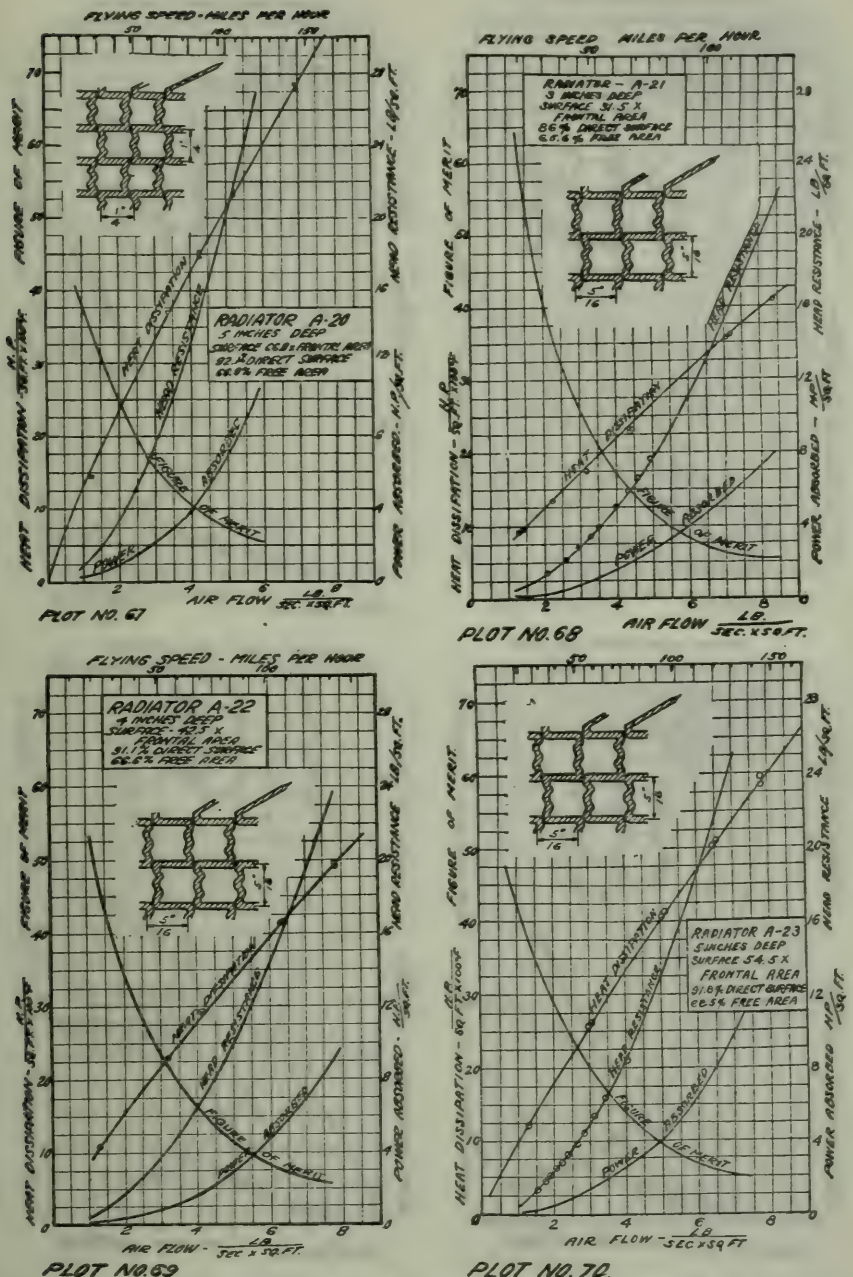
FIGS. 59–62.—*Performance curves of square cell radiator cores*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



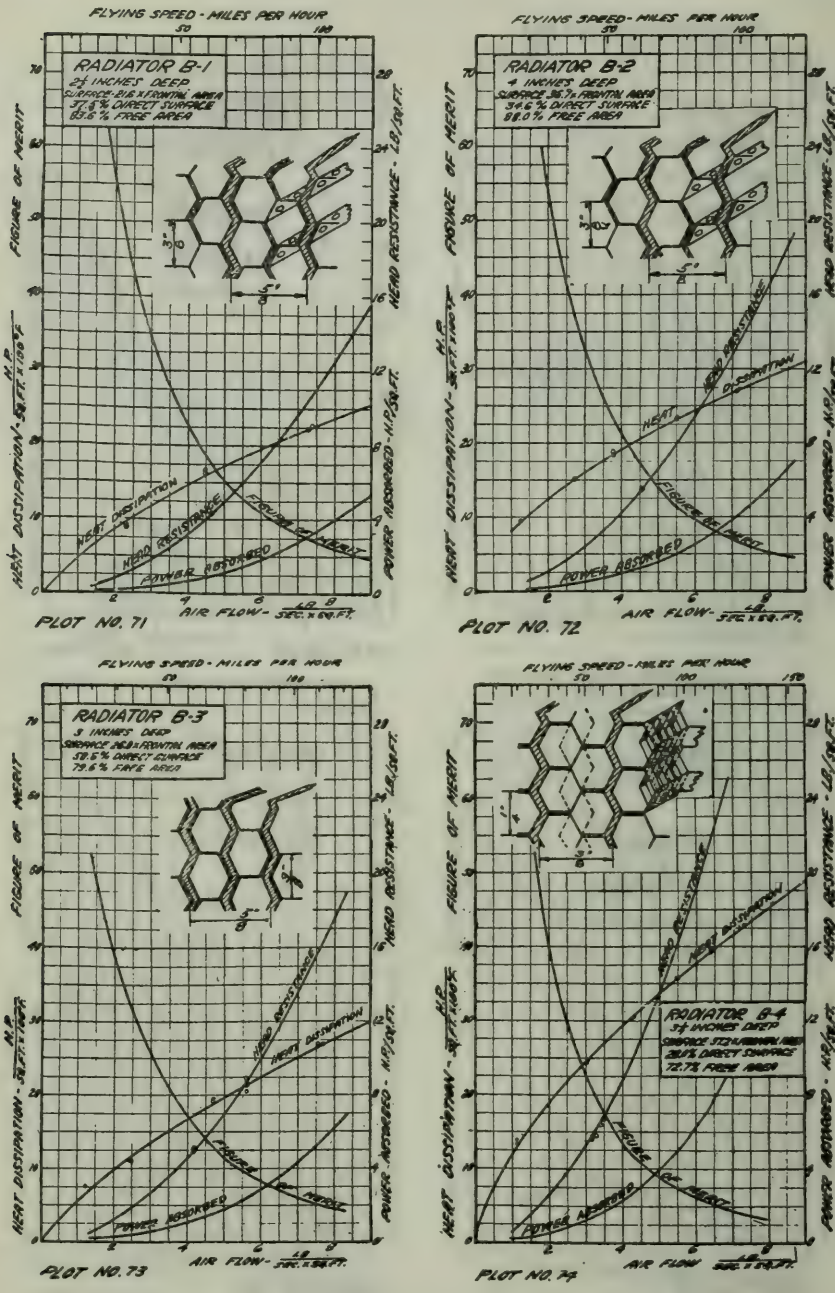
FIGS. 63–66.—*Performance curves of radiator cores with cells approximately rectangular*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



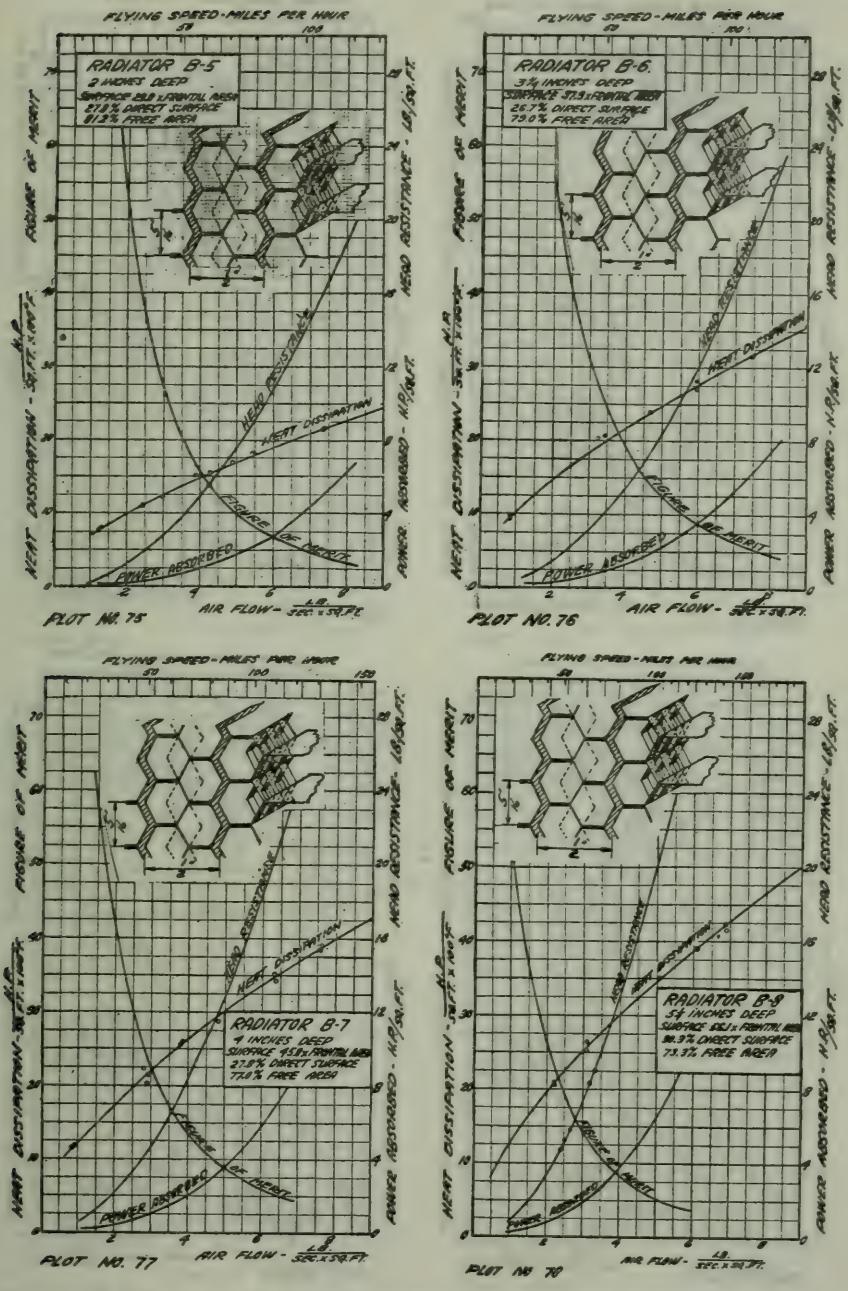
FIGS. 67–70.—*Performance curves of square cell radiator cores*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



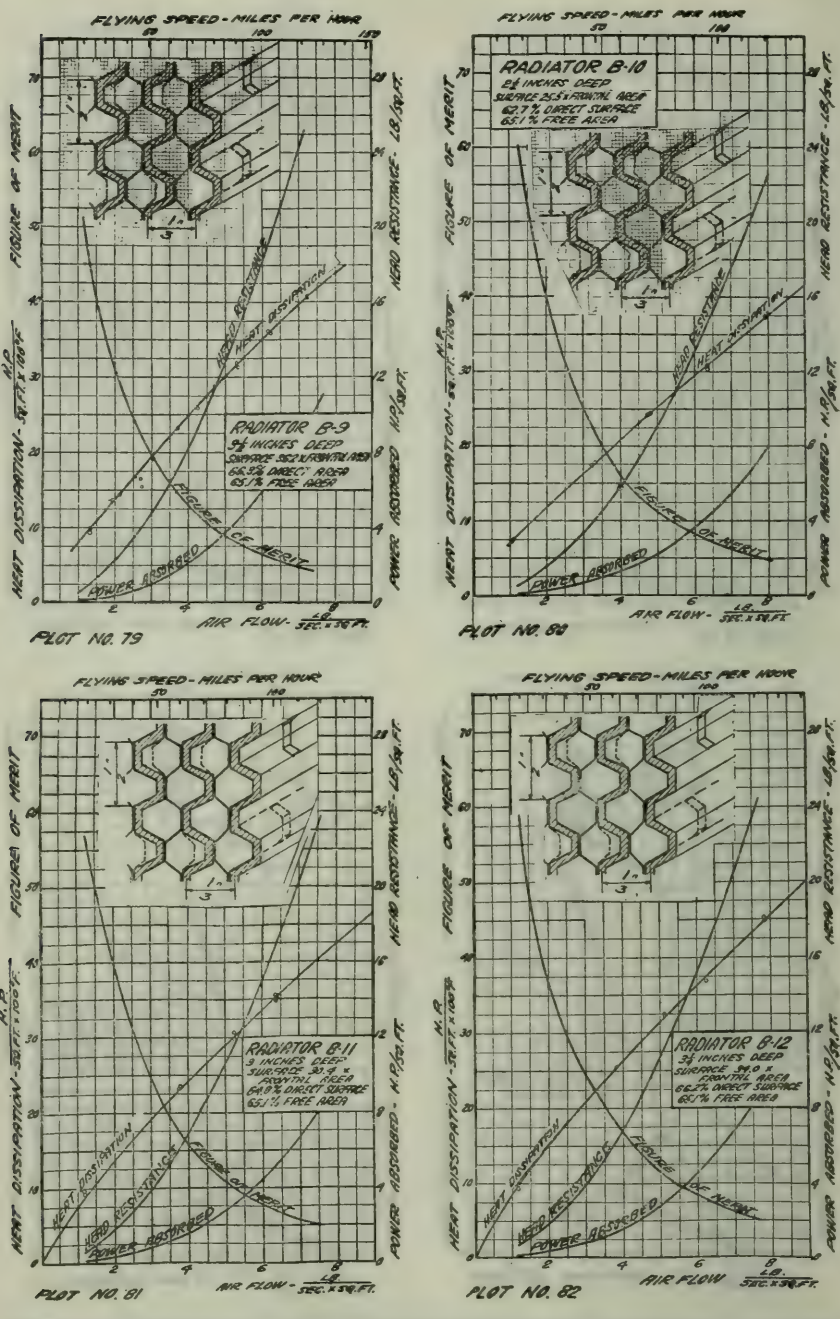
FIGS. 71–74.—*Performance curves of hexagonal cell radiator cores*

Holes interconnecting the cells in three of the above four cores modify the air flow from that for a simple honeycomb of the same size. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



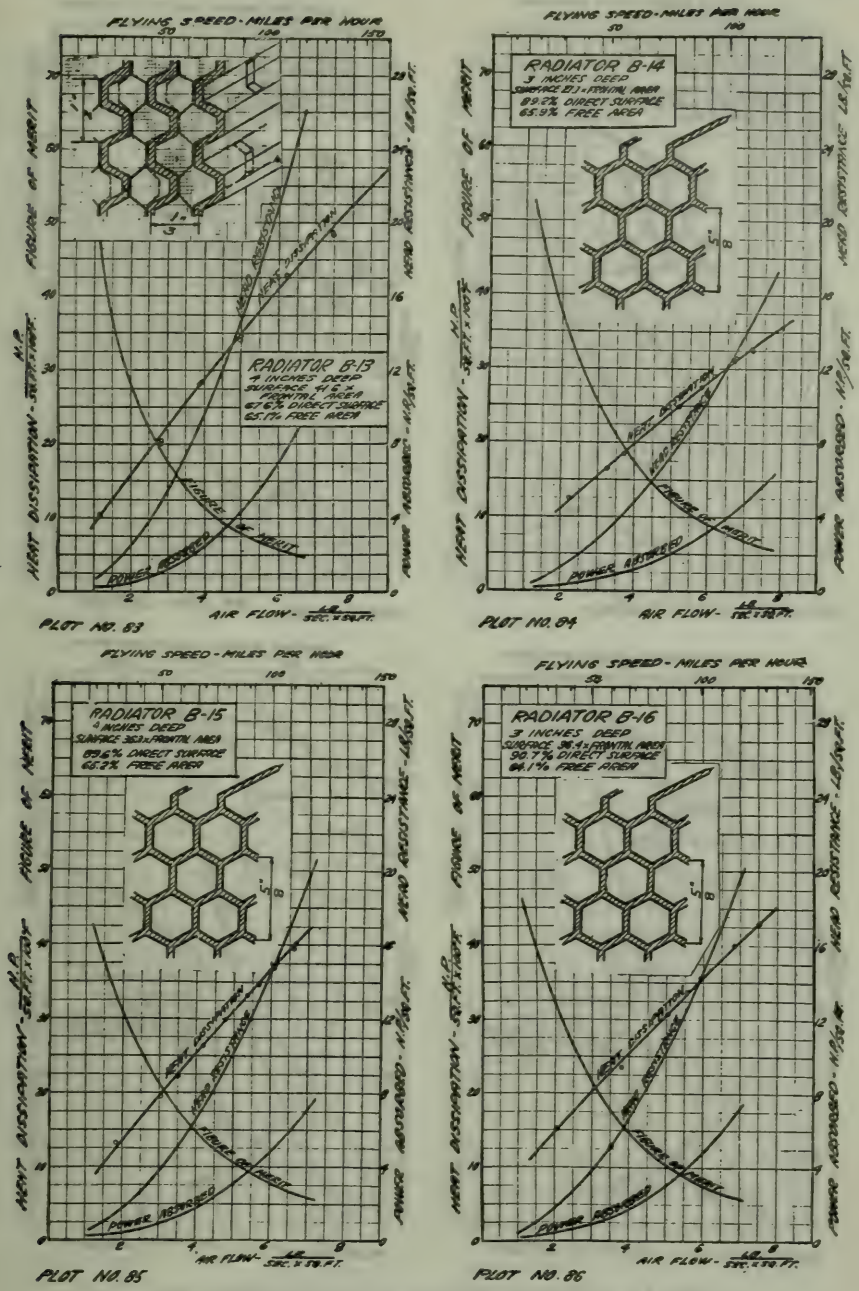
FIGS. 75–78.—*Performance curves of hexagonal cell radiator cores similar in construction to those of Figs. 71–74 except as to depth of core*

The vertical walls which are not water tubes are perforated and latticed so as to modify the air flow considerably from that in a plain hexagonal honeycomb. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



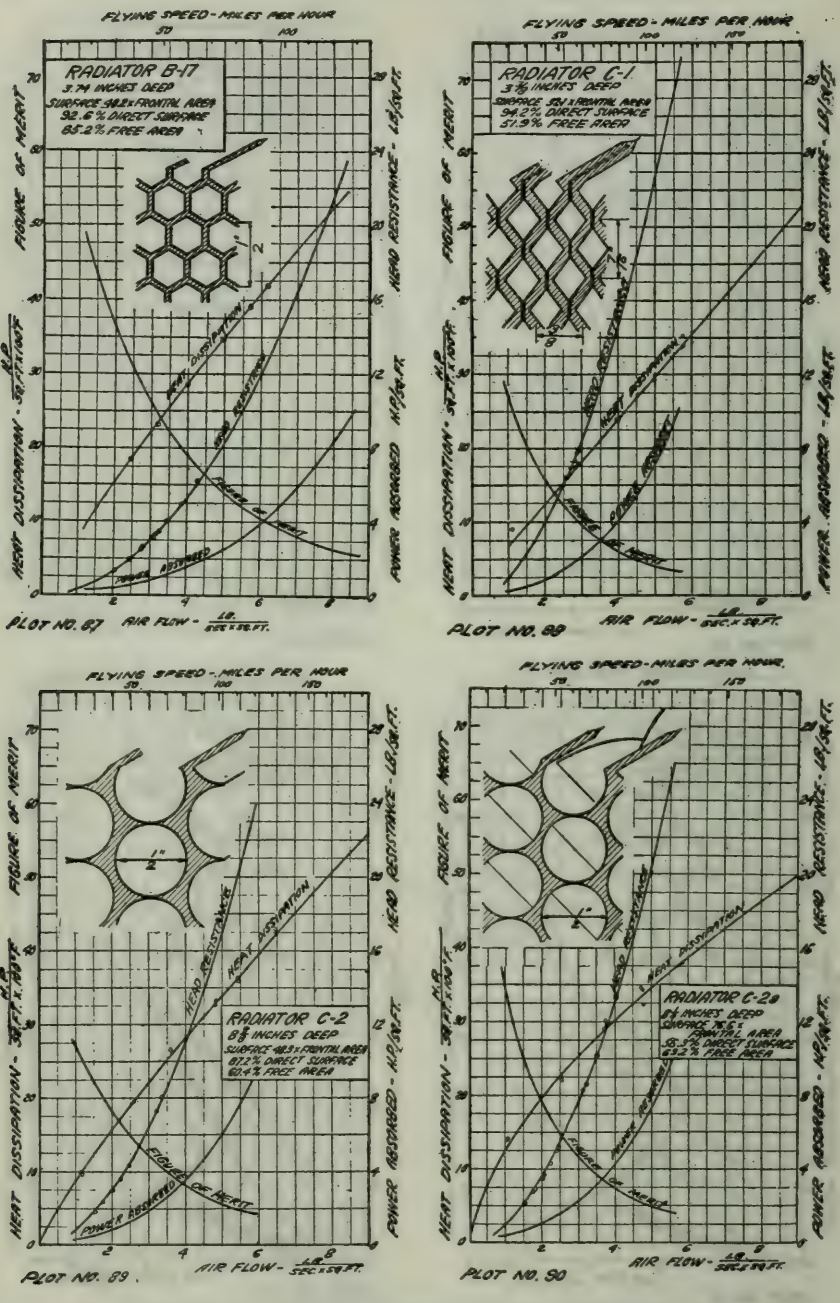
FIGS. 79–82.—*Performance curves of hexagonal cell radiator cores, similar in construction to those of Figs. 71–74, except as to depth of core*

Unlike the cores of Figs. 75–78, the air tubes are independent, but small turbulence vanes are present. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



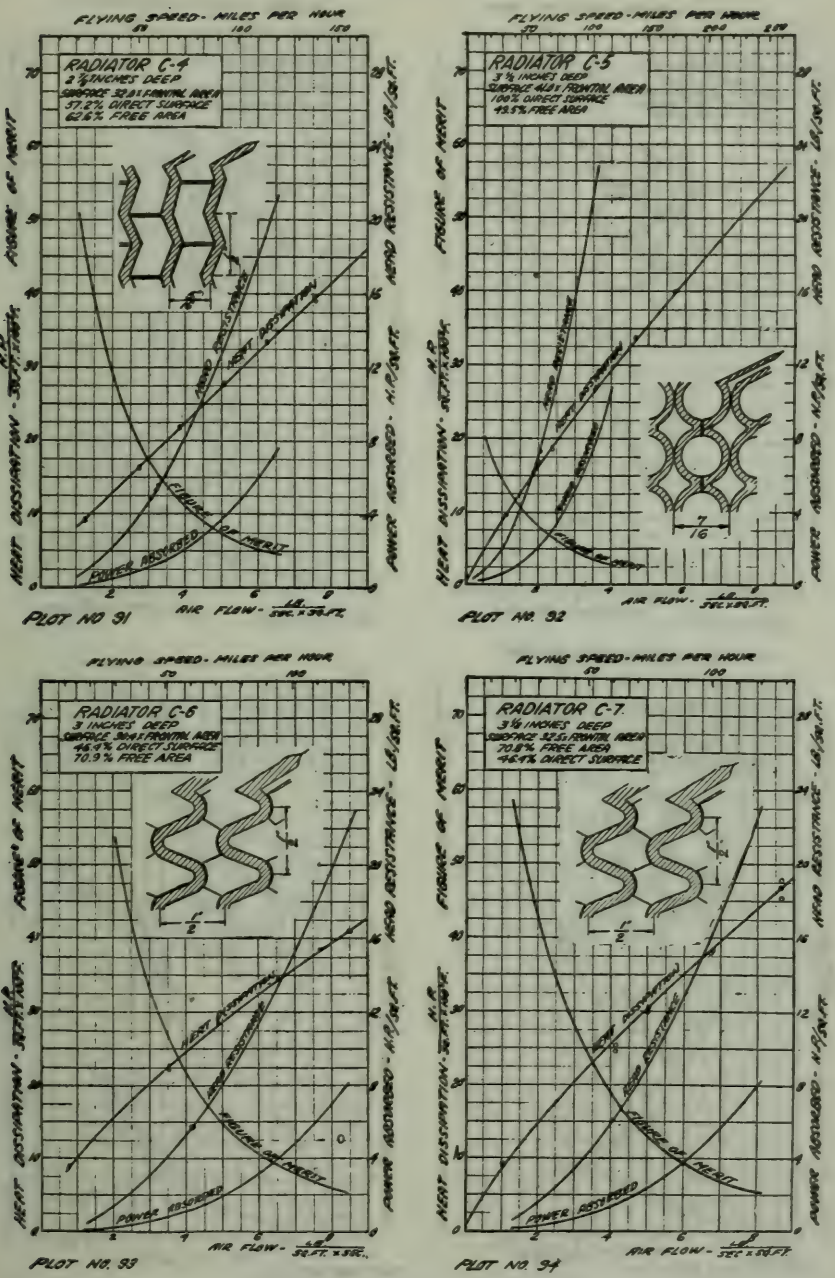
FIGS. 83–86.—*Performance curves of hexagonal cell radiator cores*

The core for Fig. 83 is of construction identical with those shown in Figs. 79–82, but deeper. The remaining three cores are of simple honeycomb construction without vanes. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4



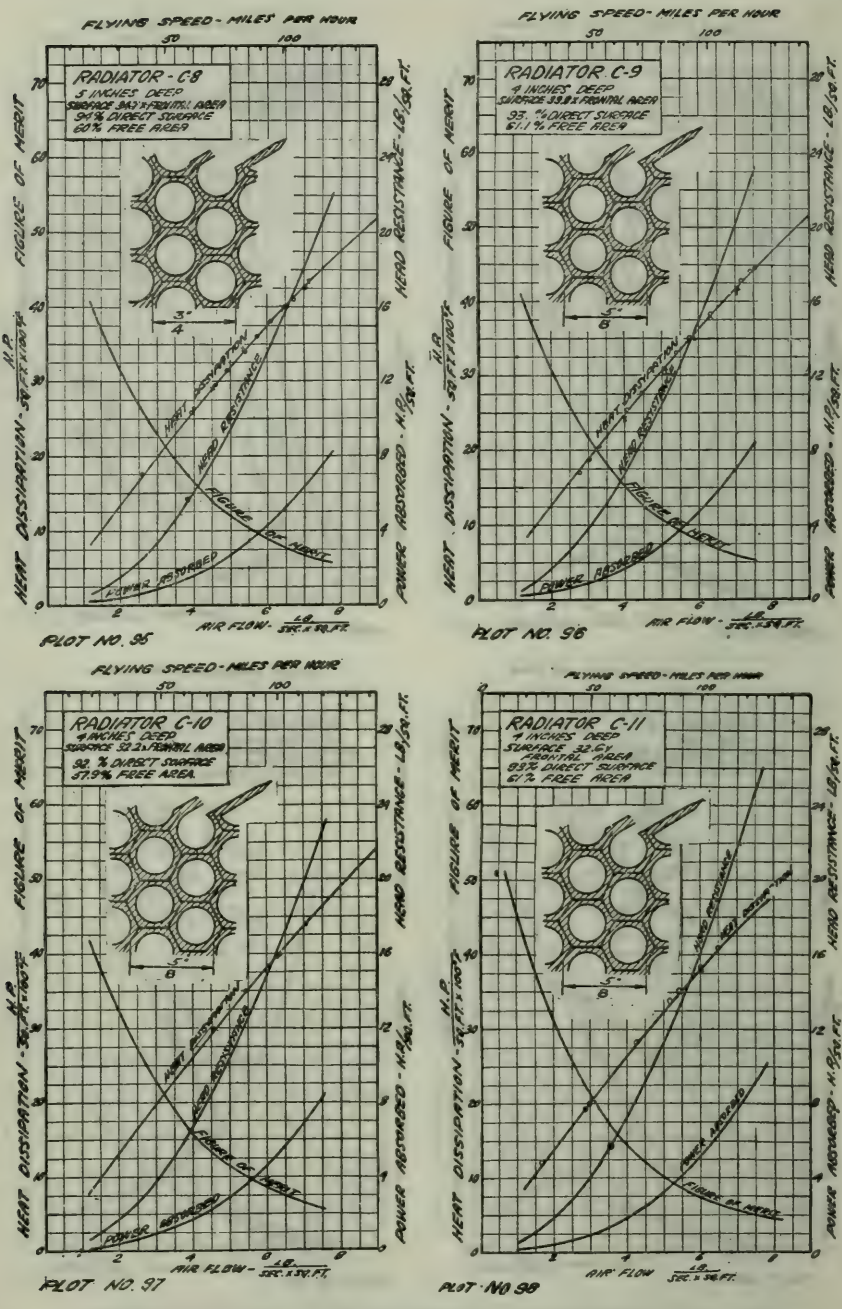
FIGS. 87–90.—*Performance curves of cellular radiator cores*

Cores C_2 and C_{2a} are identical except for a spiral turbulence vane in each air tube of C_{2a}. These reduce the air flow for given flying speed and as the curves show, figure of merit in an unobstructed position in terms of flying speed is nearly alike for both cores, the vanes introducing a slight advantage at low speeds and disadvantage at high speeds. Experimental data for these four cores are summarized in Tables 20 and 21. Units and definitions are given in Arts. 2, 3, 4



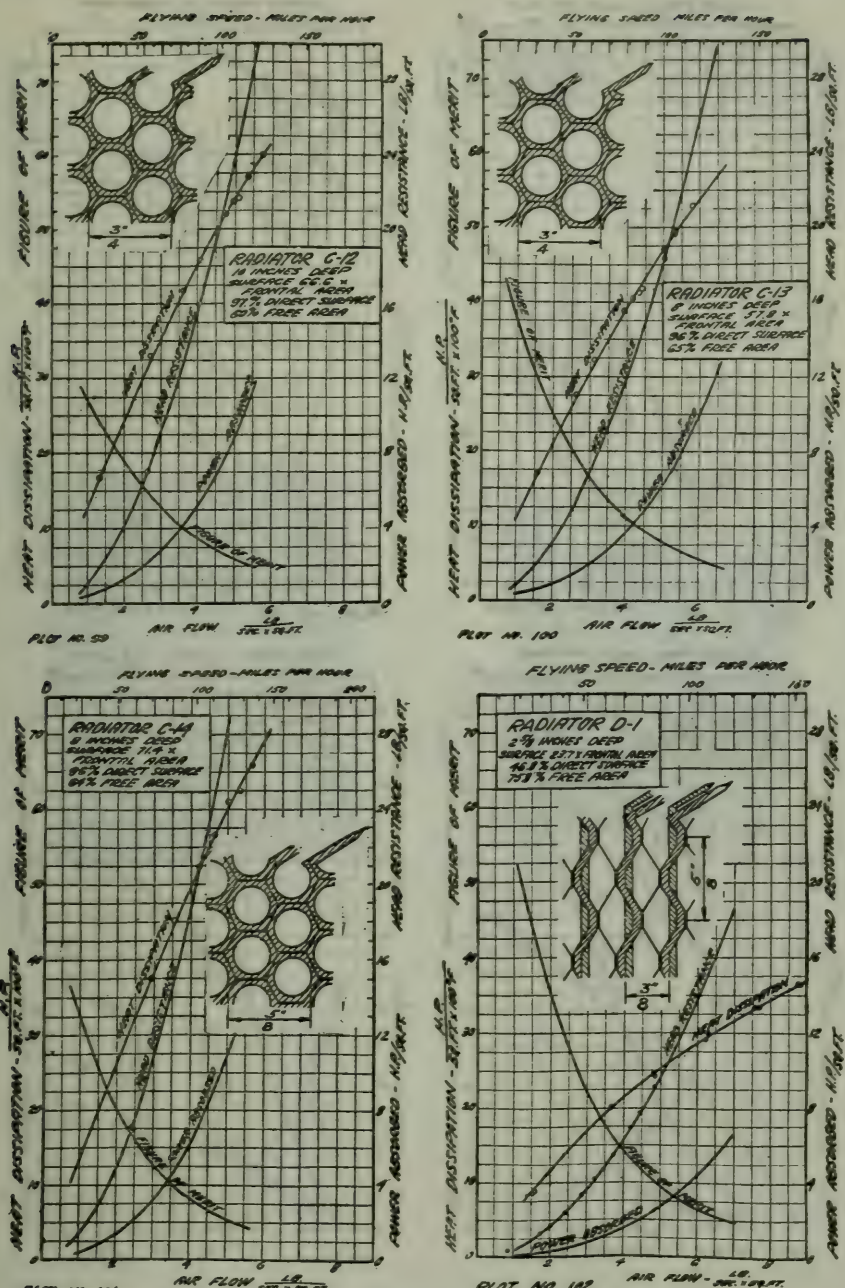
FIGS. 91–94.—*Performance curves of miscellaneous cellular radiator cores*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



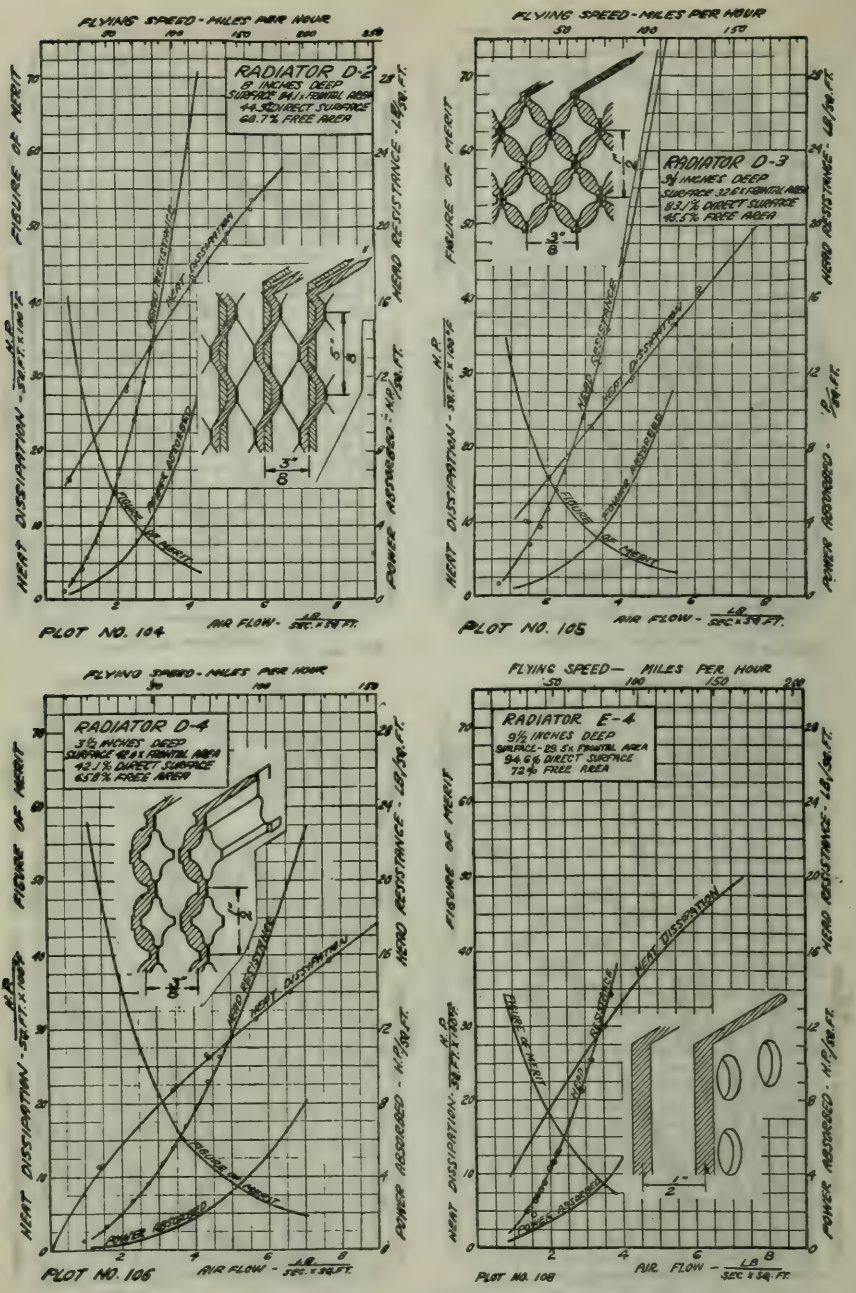
FIGS. 95–98. *Performance curves of cellular radiator cores with circular air tubes, the ends of which are pressed into hexagons for joining at the core faces*

Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



FIGS. 99–102.—*Performance curves of cellular radiator cores, the circular tube cores with hexagonal ends being similar except in depth to either C–8 of Fig. 95 or C–9 of Fig. 96*

The corrugated or dimpled form of water tube composing D–1 is not illustrated adequately by the section drawing and a photograph of the core forms Fig. 103. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



FIGS. 104–105–106–108.—*Performance curves of radiator cores*

Core D–2 (Fig. 104) is similar except in depth to D–1 (Figs. 102, 103). Core E–4 is of flat plate construction, perforated with holes which cause it to whistle in an air stream. The construction is shown in Fig. 107, a photograph of a flat plate whistling radiator. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4

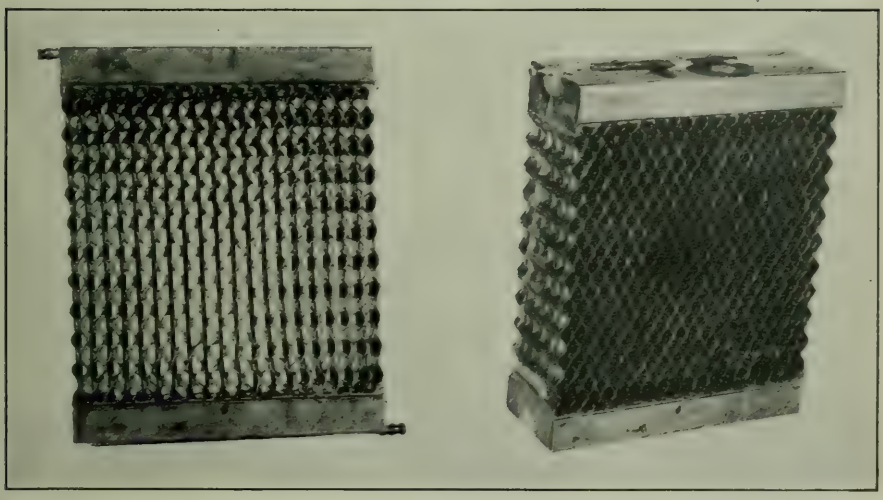


FIG. 103.—*Core section D–1 for which properties are shown in curves of Fig. 102. Core D–2 (Fig. 104) is similar construction, but deeper*

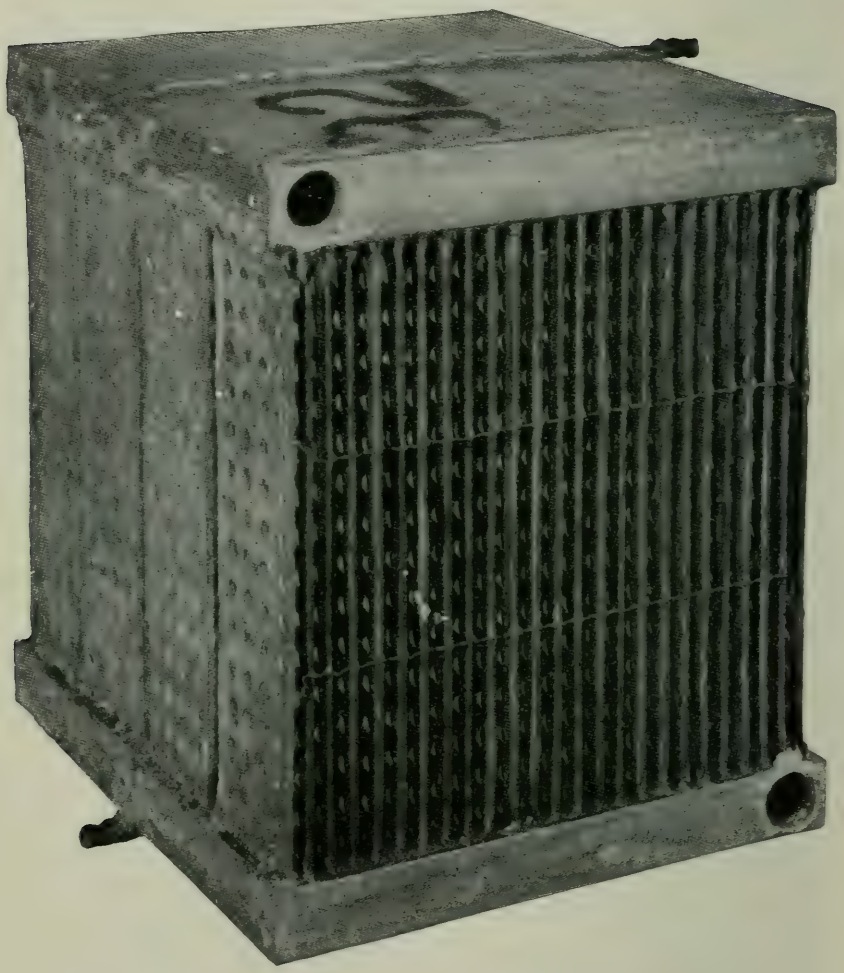
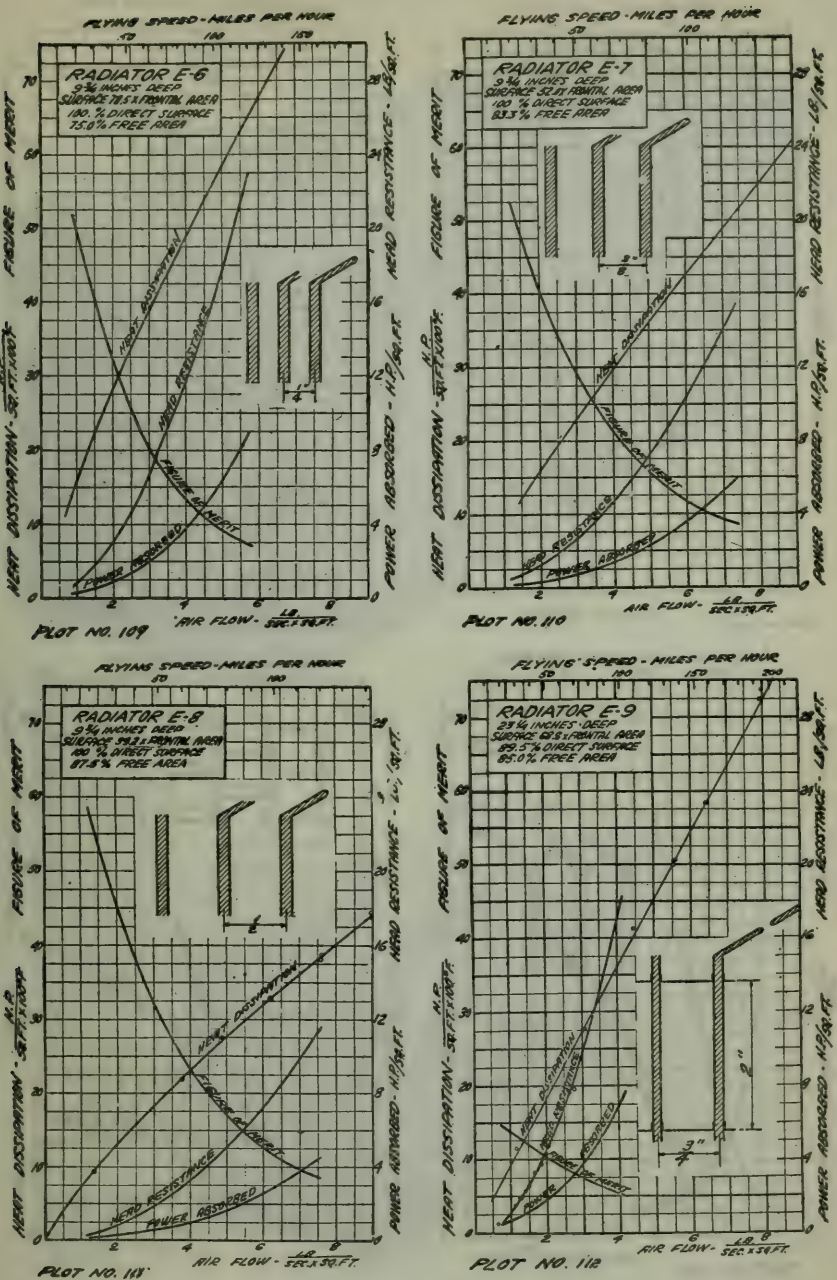


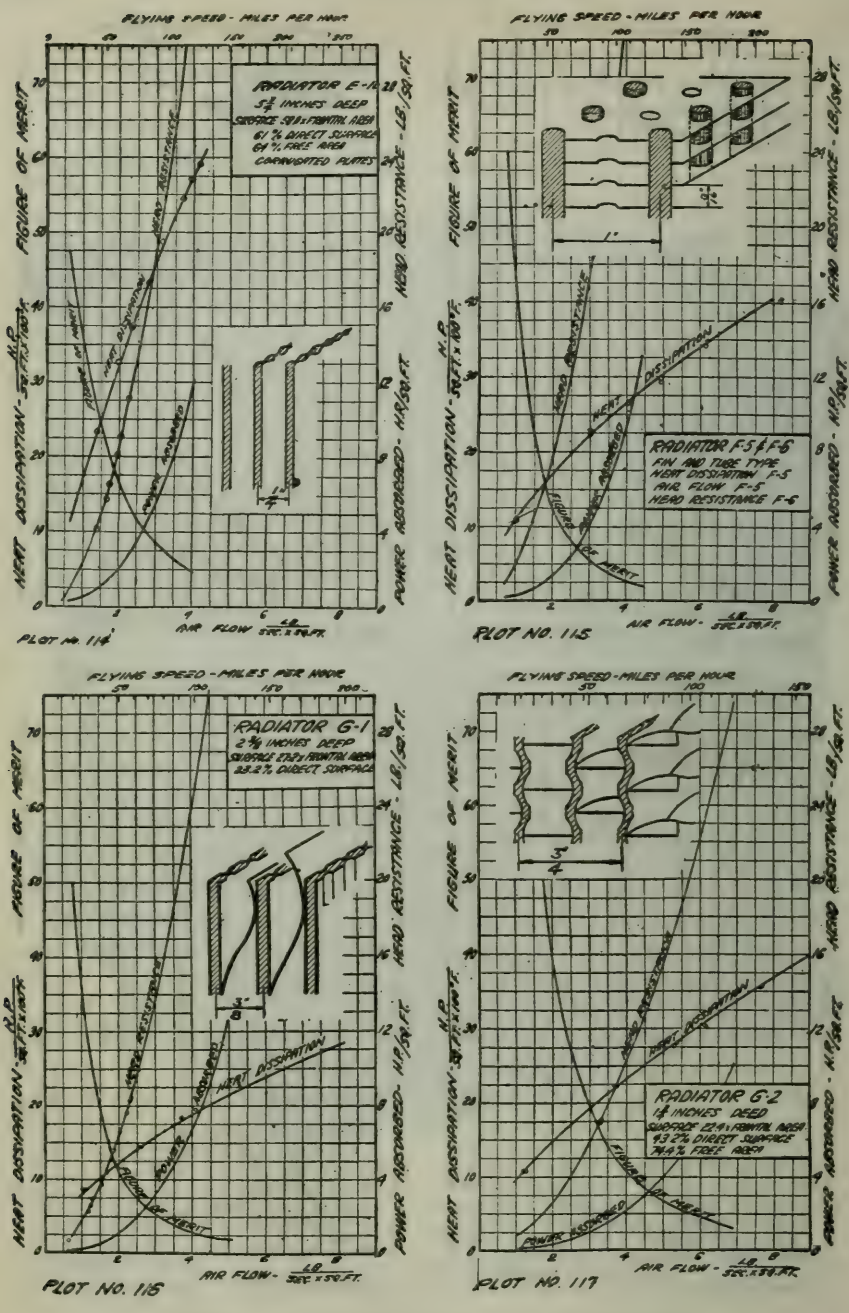
FIG. 107.—*Flat plate core E–3 with perforations in plates causing the radiator to whistle*

Cores E–1, E–2, E–3 have plates spaced 5/16 in. apart, and cores E–4 and E–5 are similar in all respects except for the more open plate spacings of 1/2 and 5/8 in. The properties of E–4 are shown in the curves of Fig. 108.



FIGS. 109–112.—*Performance of flat plate radiator cores*

This type of core shows the highest figure of merit at large flying speeds, in an unobstructed position, of any type reported in this paper. Such disadvantages as are evident are chiefly mechanical—rigidity, ease of construction and repair, etc. The construction of E–9 (Fig. 112) is illustrated by a photograph of the test specimen, Fig. 113. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4



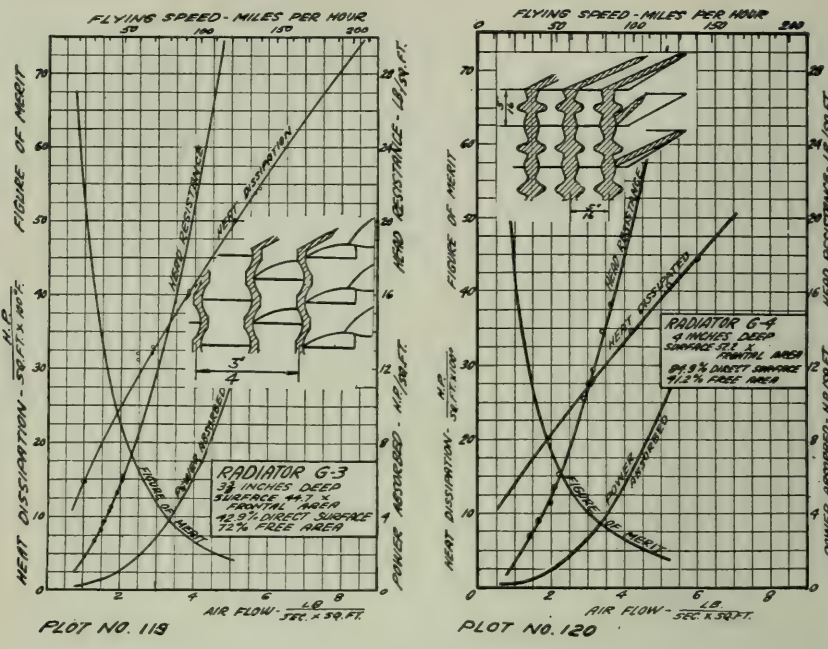
FIGS. 114–117.—*Performance curves of radiator cores*

The fin and tube type (Fig. 115), a construction which has been common in automobile use, has a figure of merit so low at large flying speeds as to discourage its use in aviation. The spiral vane construction of core G–2 (Fig. 117) is not illustrated adequately by the section drawing, and a photograph of a similar construction (G–3) is given in Fig. 118. Experimental data for these cores are summarized in Tables 20 and 21. Units and definitions may be found in Arts. 2, 3, 4

FIG. 113.—*Core section E–9 for which properties are shown in curves of Fig. 112*

FIG. 118.—*Spirex core section G–3 for which properties are shown in curves of Fig. 119*

Section G–2 (Fig. 117) exactly similar in construction, half as deep, has but one of the two sets of spiral vanes shown above



FIGS. 119–120.—*Performance curves of a spirex and a staggered cellular radiator core*

The construction of the former is shown by a photograph in Fig. 118, and of the latter in Fig. 121. Experimental data for both cores are summarized in Tables 20 and 21. Units and definitions will be found in Arts. 2, 3, 4

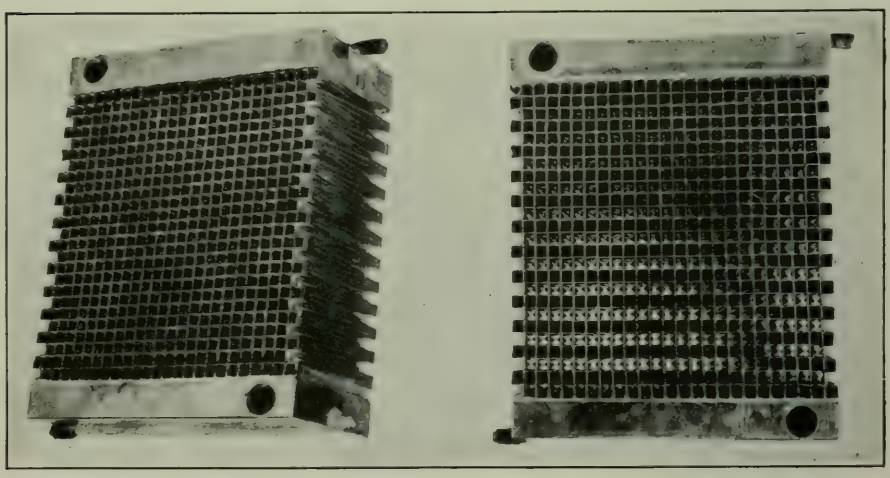


FIG. 121.—*Core section G–4 for which properties are shown in curves of Fig. 120. The staggered arrangement of the tubes is shown in the perspective view at the right*

VIII. APPENDIXES

APPENDIX A

110. General Notation

a=free area of radiator core.

b=any constant; constant in equation $H=bM^n$; width of fin.

C_p=specific heat of air or steam at constant pressure.

c=conversion factor; constant in equation $R=c\,S^2$; correction for humidity, article 12.

D=diameter of tube.

E=effectiveness of indirect cooling surface; e. m. f. from thermocouples.

e=base of Napierian logarithms.

F=figure of merit.

f=sign of a function.

g=acceleration of gravity.

H=heat dissipated, $\frac{\text{h. p.}}{\text{sq. ft.}\times 100^\circ\text{ F.}}$ or $\frac{\text{kw}}{\text{m}^2\times 50^\circ\text{ C}}$

H, with subscripts=heat dissipation in other units or particular values of H.

k=any constant; constant in equation $M=k\,S$; thermal conductivity.

l=length.

M=air flow, $\frac{\text{lb.}}{\text{sec}\times\text{sq. ft.}}$ or $\frac{\text{kg}}{\text{sec}\times\text{m}^2}$

m=air flow constant.

n=exponent of equation $H=b\,M^n$; number of plates per unit width in flat plate radiators; general symbol for exponent in a few other special applications.

P=power absorbed; an integral used in calculation of air flow constant.

p=pressure, with subscripts; perimeter of air tubes.

q=surface coefficient of heat dissipation, heat per unit time per unit surface per unit temperature difference.

R=head resistance; head resistance chargeable to the radiator.

r=hydraulic radius; lift-drift ratio; relative humidity.

S=flying speed.

T=temperature difference between air and water; absolute temperature.

t=time.

u=see article 68.

v=velocity.

w=weight of core and contained water; weight of steam condensed.

x=depth of radiator; distance along air tubes; gage readings; differential pressure of pitot tube gage.

y=thickness of fin.

α=see article 63.

ρ=air density.

APPENDIX B.—TURBULENCE IN AIR TUBES

111. Experimental Methods Used.—No attempt is here made to take up the questions of turbulence from a theoretical standpoint, but a brief record of experimental evidence bearing on the problems is presented,[31] together with certain con-

[31] A detailed record of these experiments has been published as Technical Report No. 106, National Advisory Committee for Aeronautics.

clusions that seem to be warranted by the evidence, namely, that turbulent flow is found in the tubes of ordinary radiators at usual speeds, and that there are differences in nature or degree of turbulence in different radiators. Three general methods may be used for detecting turbulence—a visual method using some kind of smoke, measurements of pressure gradients, and measurements of heat transfer or of temperature.

The visual method has great advantages, but is inconvenient for work inside of the radiator because of the difficulty of arranging the apparatus so that it shall not disturb the flow of air and at the same time so that the air currents in the radiator tubes may be distinguished from currents before and behind it. The fact that the pressure gradient along an air stream is approximately proportional to the first power of the speed for stream line or viscous flow and to the square of the speed for turbulent flow may be used to determine the nature of the stream. The transfer of heat from a surface swept by a stream of air depends upon the turbulence of the stream as well as upon its velocity, and while with the present limited knowledge of coefficients of heat transfer, a single measurement might be of little value for detecting the presence or absence of turbulence considerable information may be gained from comparative measurements. Temperature measurements at different points in a stream of air that is being heated or cooled may, if reliable, furnish some indication of the condition of the air by showing how heat is transmitted through different portions of the stream.

The experimental work on which the conclusions are based was done in a 20 cm (8-inch) square wind tunnel, and the evidence here presented is not sufficient for a confident answer to the question whether the same kind of flow is found in a stationary radiator with air blowing through it as in a radiator moving through still air. It seems to be shown conclusively, however, that, at least when the radiator is in the wind tunnel, there are characteristic conditions of turbulence in different types of core, and it seems reasonable to suppose that such characteristic conditions would also be found in radiators moving through still air. The experimental work undertaken for the investigation of turbulence in radiator tubes includes the following parts:

I. Pressure gradients in radiator tubes.
II. Cooling coefficients of radiators.
III. Cooling of wires in an air stream.
IV. Temperature gradients.

112. Pressure Gradients.—An indication of turbulent flow is given in Table 2 (art. 17) by the agreement between the power of the air flow to which the pressure gradient is proportional and that computed by the Lees formula for turbulent flow in long tubes.

113. Surface Heat Dissipation Coefficients of Radiators.—The coefficient q of Table 21, which represents heat dissipated per unit time per unit surface per unit temperature difference at an average speed of 100 feet per second (30 m per sec) through the tubes, varies widely between different types of radiators. Reference to the table will show that the coefficient ranges (using the English units) from 0.7 to 1.1 for radiators whose air passages have straight, smooth walls, from 0.7 to 1.1 for pseudocellular types, from 1.0 to 2.2 for perforated plate types that whistle in an air stream, and for a type with spiral vanes is 1.3. In general, the coefficient decreases as the size of the cell increases.

The wide range of coefficients even for straight tubes, the high coefficient for the section with spiral vanes, and the very high values found with some of the perforated plate types appear to be very strong evidence of varying conditions of turbulence in the different classes. The presence of a peculiar turbulence in the perforated plate types is also indicated by their whistle.

Coefficients for the radiators with true circular air tubes (type C–2) if computed by the equation of Nusselt [32] would be 0.0031, the observed value for C–2 at the same air speed being 0.0024. Nusselt's equation represents conditions with turbulent flow in

[32] Zeitschrift des Vereines Deutscher Ingenieure, 53 II, 1909, p. 1811; 54 II, 1910, p. 1154.

the central portions of long tubes, whence its application to radiator tubes is somewhat open to question.

114. Cooling of Wires in an Air Stream.—The temperatures maintained by electrically heated wires connected in series so that each should carry the same current were used for a comparison of the cooling effect of the small streams of air flowing through a cold radiator with that of the stream in the wind tunnel in front of it.

Two pieces of 0.1 mm (0.004 inch) platinum wire, each about 6 cm (2.4 inches) long and separated by 48 cm (19 inches) of No. 36 copper wire, were strung by copper leads straight along the channel, so that one wire was in the stream some distance in front of the radiator, while the other was in one of the tubes, well back toward the rear face. The platinum wires, connected in series with a current-measuring shunt, as shown in Fig. 122, were heated by a small electric current and the potential drop across each platinum wire and across the shunt measured with a potentiometer. In order that the wires might disturb the air flow as little as possible, the potential and current leads were laid side by side (not twisted) and shellacked together for some distance from the platinum wires. The current leads supporting the wires were

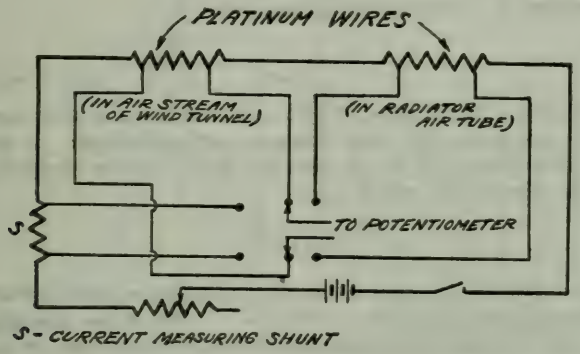


Fig. 122.—*Diagram of electrical connections for the comparison of the cooling effect of the air stream in a radiator air tube and the cooling effect of the open stream in the wind tunnel some distance in front of the radiator core*

Platinum wires in each of the two positions were heated by the same current and their equilibrium temperatures were measured by their resistances, obtained by a potentiometer method

passed over rods set across the channel about 55 cm (22 inches) in front of and behind the radiator and out through small holes in the floor of the wind tunnel. The resistances when unheated were measured with small currents (about 0.006 ampere) and in an air stream of velocity about 13 meters per second (30 miles per hour). It seemed hardly worth while to attempt to use the wires as resistance thermometers to the extent of measuring the temperatures to which they rose, but since for small temperature changes the resistance of the platinum wire is roughly proportional to the absolute temperature, the fractional increase in resistance of each wire was used as a rough measure of its rise in temperature on being heated.

Heat dissipation from fine wires to moving fluids has been found to be proportional to the temparature difference and the square root of the velocity for a silver wire in a tube of flowing water;[33] and for a platinum wire moved through air on a whirling arm,[34] and if the same relation is assumed for the present case, a factor depending upon the turbulence may be found as follows: The relation may be expressed by the equation

$$H = c\theta\sqrt{v} \qquad (1)$$

[33] Rogovsky, Comptes Rendus, 136, June 8, 1903, p. 1391.
[34] King, Philosophical Transactions of the Royal Society of London, A214, 1914, p. 373.

where H=heat dissipated from the wire in units of power per unit length of wire.
θ=temperature difference between wire and air.
v=linear velocity of air past wire.
c=a coefficient which includes a factor representing degree or nature of turbulence.

The air velocity is greater past the rear wire than past the front wire, because the radiator restricts the cross section of the stream and

$$v_2=\frac{v_1}{a} \tag{2}$$

where a=the fractional part of the frontal area of the radiator that is open for the passage of air, called its "free area."

and the subscripts 1 and 2 represent the front and rear wires, respectively. Turbulence at the front wire—i. e., in the open channel of the tunnel—is represented by the coefficient

$$c_1=\frac{H}{\theta_1\sqrt{v_1}} \tag{3}$$

and at the rear wire—i. e., in the radiator tube—by

$$c_2=\frac{H}{\theta_2\sqrt{v_2}}. \tag{4}$$

The heat dissipation H is the same in both cases, because the wires carry the same current and are practically the same resistance per unit length. A comparison of turbulence in the radiator with that in front of it is obtained by substituting equation (2) in (4) and dividing by (3), which gives

$$\frac{c_2}{c_1}=\frac{\theta_1}{\theta_2}\sqrt{a}.$$

As indicated above, the per cent of increase in resistance on being heated is used as a rough measure of the temperature difference θ. The values, including the ratio of the coefficients, are shown in Table 22 and indicate differences in turbulence in different types of radiator with the greatest turbulence in the perforated plate type, which whistles in an air stream.

TABLE 22.—Comparison of Turbulence by Relative Cooling of Two Wires in the Air Streams

(1) In open channel of wind tunnel, (2) in the air tube of a radiator core

Type of radiator	Air speed (approximate)	Current	Per cent increase in resistance		Free area a	Ratio of coefficients $\frac{\theta_1}{\theta_2}\sqrt{a}$	Mean ratio
			Front θ_1	Rear θ_2			
	m/sec.	amp.	Per cent	Per cent	Ratio		
Flat plate	13	0.285	2.3	2.1	0.88	1.05	.....
	13	.457	8.1	7.8	.....	.98	.....
	18	.456	7.4	7.0	.....	1.00	1.01
Circular cell	13	.485	9.6	9.5	.65	.81	.....
	17	.472	9.3	8.5	.....	.88	.....
	13	.304	3.7	3.3	.....	.90	.....
	17	.303	3.6	3.3	.....	.88	.....
	17	.497	9.9	9.0	.....	.83	.87
Perforated plate	18	.208	.8	.5	.88	1.7	.....
	18	.407	5.9	4.4	.....	1.26	.....
	13	.404	5.5	4.0	.....	1.30	.....
	13	.448	7.6	5.6	.....	1.29	1.30

115. Temperature Gradients in Air Tubes.—In order to obtain some indication of the distribution of temperature within the air passages of radiators, the following procedure was followed: A section of radiator was mounted in the 20-cm (8-inch) wind tunnel and hot water was pumped through it as in calorimetric tests. A copper-constantan thermocouple was strung through one of the air tubes of the radiator and supported by its own copper leads in the manner described above for the platinum wires. The constantan wire was about 30 cm (12 inches) long, and the cold (upstream-junction was outside of the radiator in the stream of incoming air, when the hot (down) stream) junction was in any measured position in the radiator tube or even somewhat behind the rear face. Screw threads, with a pitch of 0.16 cm (1/16 inch) on the rods

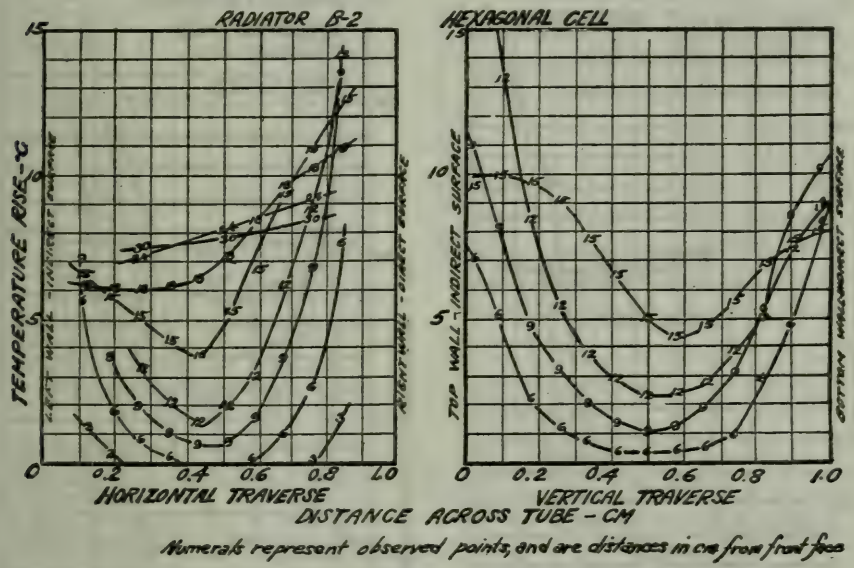


Fig. 123.—*Temperature gradient across air tube of a hexagonal cell radiator in several planes at intervals of 3 cm*

The numerals represent observed points and indicate the distances of the respective planes back from the front face of the radiator. The core is 10.2 cm deep, and mapping of the gradients was continued far beyond the rear face of the radiator, the last plane shown in the figure being 30 cm back of the front face. The vertical boundaries of the plot mark the position of the walls of the air tube. Average water temperature was 55° C above entrance air temperature, but the tube walls formed by indirect cooling surface were at temperatures somewhat lower. Lack of symmetry in horizontal traverse is due to the fact that the right wall is direct and the left indirect, cooling surface. Lack of symmetry in vertical traverse is probably due to a slight error in alignment of radiator and thermocouple wire

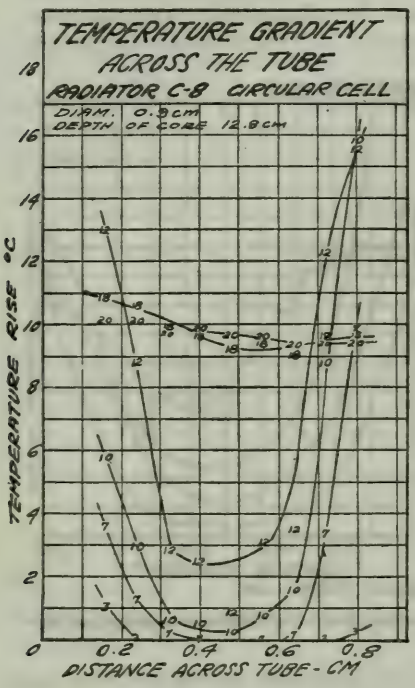
supporting the wires and on the supports for the rods, furnished rough micrometers for setting the position of the thermocouple and for moving it horizontally and vertically.

The mean temperature difference between the water in the radiator and the air passing through it and the speed of the air stream were maintained approximately constant, and corrections for variations in the temperature difference were made on the assumption that the temperature rise indicated by the thermocouple was proportional to this difference. No correction was made for slight fluctuations in the speed of the air stream, for trial showed that the effect on the thermocouple readings was small, even when the speed was varied over a wide range.

In order that the air might be disturbed as little as possible, fine wires were used and were bared for some distance each side of the constantan section. At first wire of

diameter 0.10 cm (B. & S. gage 38) was tried, but so much trouble was experienced with breakage that most of the work was done with wire of diameter 0.13 cm (B. & S. gage 36).

Figures 123–5 show temperature gradients across the center of the tubes in four radiators, in planes at different distances from the front face, the sides of the plots representing the walls of the tubes. Figs. 126–7 show isothermal lines in a diameter plane of an air tube plotted from the data shown on the other curves, and the upper



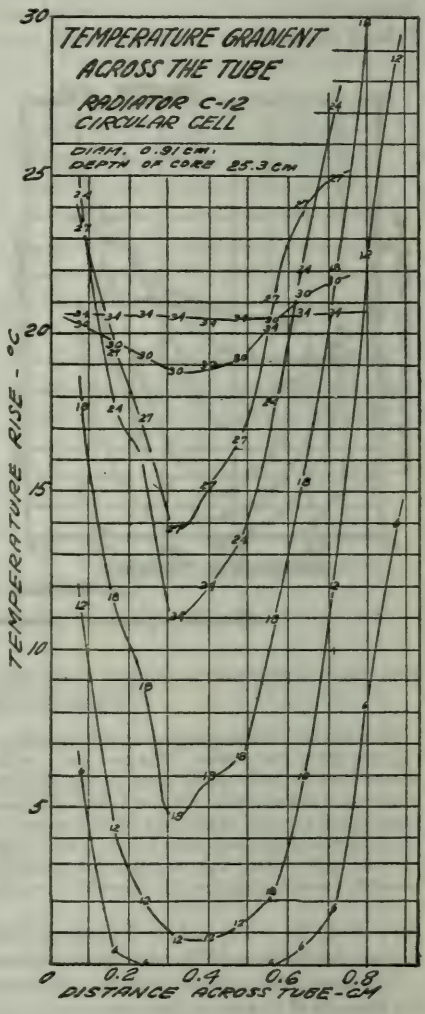


FIG. 124.—*Temperature gradients across air tubes of circular cell radiators, in several planes at different distances back from the front face of the core*

The numerals represent observed points and indicate the distance of the respective plane back of the front face. It will be noted that gradients are mapped in the open wind stream in planes considerably back of the back faces of the cores. The vertical boundaries of the plots mark positions of the walls of the tubes. Average water temperature 55° C above temperature of air entering the core

and lower sides of the plots indicate the walls of the tubes. It must be emphasized that the quantities shown on the curves are very rough values and can be used quantitatively only with very great caution, if at all, because the steepness of the temperature gradients across the tube and the uncertainty in the position of a thermoelectric junction suspended by a meter of fine wire in an air stream make individual readings quite unreliable. Indeed, the uncertainty of position made it impossible to duplicate readings with any accuracy after the wires had been moved forward or backward, and readings were accordingly taken across the tube from one side to the other before

moving the thermocouple to a new position along the stream. But, although individual readings are not very reliable, the qualitative indications of the plots are probably correct.[35]

It has been suggested that at sections of the tubes near the forward end both viscous and turbulent flow might exist, each occupying a certain part of the cross section. If such were the case, a sudden break would be expected in the temperature gradient across the tube, at the boundary between the two kinds of flow, but no indication of

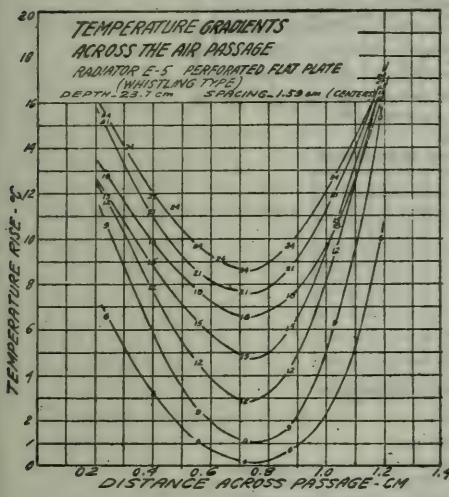


FIG. 125.—*Temperature gradients across air passages of a flat plate core construction, with perforations in the plate (whistling type)*

The numerals represent observed points and indicate the distance back from the front face to the plane in which the gradient is mapped. The vertical boundaries of the plot indicate the position of the side walls of the air passage. The average water temperature was 55° C above the temperature of the air at the front face of the radiator

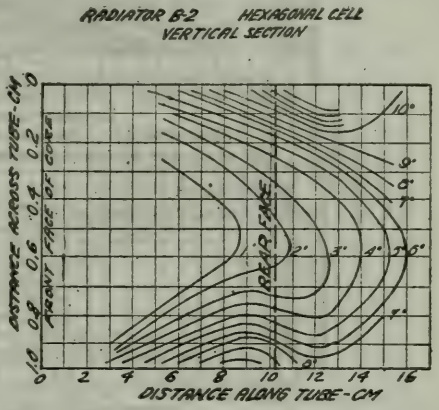


FIG. 126.—*Isothermal lines in the vertical diameter plane of an air tube of a hexagonal cell radiator core*

Plotted from data shown in Fig. 123. Lack of symmetry is chargeable to the inaccuracies of reading described in Article 114. Average water temperature 55° C above temperature of air entering the core

such a break is found in the data; and, although the inability to get reliable readings very close to the walls (because of contact between the swinging thermocouple wire and the wall) might have concealed this condition in some parts of the tubes, it seems reasonable to suppose that it would have been detected at least in the longest tube.

The curves are of the form characteristic of turbulent flow and are similar to curves of temperature gradients [36] and isothermal lines [37] found by other observers when working with long tubes at velocities well above the critical value.

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[35] The possible effect of errors due to lead conduction in the thermocouple was investigated and found to be entirely negligible in comparison with the known errors due to uncertainty of position.

[36] T. E. Stanton and Dorothy Marshall, British Advisory Committee for Aeronautics, Reports and Memoranda, No. 243, June, 1916.

[37] Groeber, Zeitschrift des Vereines Deutscher Ingenieure, 56, March, 1912, p. 421.

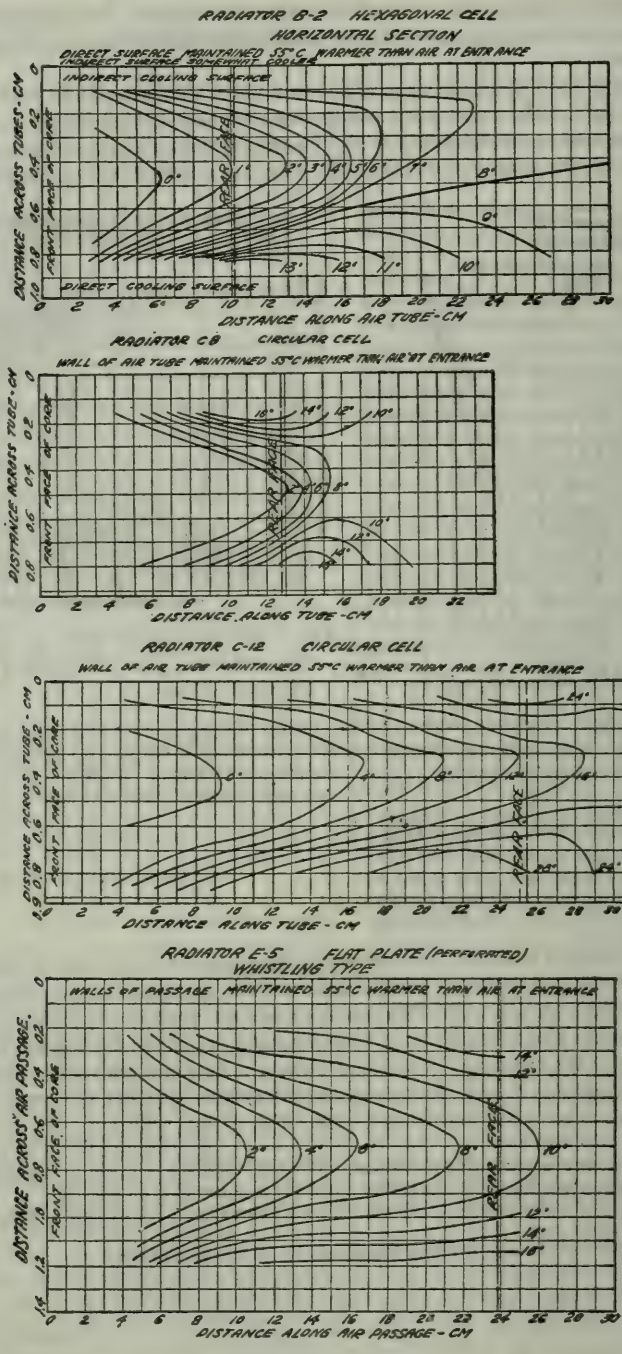

FIG. 127.—*Isothermal lines in a horizontal diameter plane of an air tube for different types of core. Plotted from data shown in Figs. 123–125*

APPENDIX C.—REDUCTION FOR AIR DENSITY IN COMPUTATION OF AIR-FLOW CONSTANT

116. Extending the notation of article 17, let

M=air flow, units of mass per unit time per unit frontal area of radiator,

M_0="unobstructed" air flow in open wind tunnel,

ρ=air density,

Q=pressure difference between two points in the air tube of the radiator core,

b', n=constants for each radiator,

c=calibration factor of the pitot tube, including the usual coefficient of the tube and conversion factors incident to units chosen,

h=reading on pressure gage,

and let the subscripts 1 and 2 denote the closed or steam tunnel and the open 54-inch tunnel, respectively. (In the tunnel (1) the radiator core fills the wind channel completely, so that the entire wind stream is forced to pass through the core; in (2) the relative transmission through the core and deflection around it are conditioned by the core construction.)

By equation (6), article 17,

$$Q_1=b'\frac{M^n_1}{\rho_1} \tag{1}$$

and

$$Q_2=b'\frac{M^n_2}{\rho_2}. \tag{2}$$

In the steam tunnel Q_1 and M_1 are measured, and equation (1) may be solved for b', giving

$$b'=\frac{Q_1\rho_1}{M^n_1}. \tag{3}$$

Solving equation (2) for M_2,

$$M_2=\sqrt[n]{\frac{Q_2\rho_2}{b'}} \tag{4}$$

and substituting (3) in (4)

$$M_2=\sqrt[n]{\frac{Q_2\rho_2}{Q_1\rho_1}}M_1. \tag{5}$$

Now, the air flow constant is by definition

$$m=\frac{M_2}{M_0} \tag{6}$$

and the equations of the pitot tubes may be put in the forms

$$M_1=c_1\sqrt{\rho_1 h_1} \tag{7}$$

$$M_0=c_2\sqrt{\rho_2 h_2} \tag{8}$$

Substituting (7) in (5) and (8) and (5) in (6),

$$m=\sqrt[n]{\frac{Q_2\rho_2}{Q_1\rho_1}}\,\frac{c_1}{c_2}\sqrt{\frac{\rho_1 h_1}{\rho_2 h_2}} \tag{9}$$

In the computation as outlined in article 17 it is assumed that $\rho_1=\rho_2$ and the error introduced in this equation by that assumption is evidently indicated by the quantity

$$\sqrt[n]{\frac{\rho_2}{\rho_1}}\sqrt{\frac{\rho_1}{\rho_2}}=\left(\frac{\rho_2}{\rho_1}\right)^{\frac{2-n}{2n}}.$$

The value of n hardly ever falls below 1.7, and a change in density from 0.0750 to 0.0700 pounds per cubic foot represents a wide variation in conditions. For this extreme case the correction factor becomes

$$\left(\frac{0.0750}{0.0700}\right)^{0.09}=1.006.$$

APPENDIX D.—TEMPERATURE DROP IN WATER-TUBE WALLS

117. To support the statement of article 58 that the temperature difference between inside and outside of water-tube walls is small in comparison with the temperature difference between air and water, an estimate of the magnitude of the drop in the metal may be made by estimating the heat transfer, assuming an amount of cooling surface and computing the temperature head necessary to force heat through various thicknesses of metal at the estimated rate.

As an extreme case, assume a flying speed of 200 miles per hour, or 89.4 meters per second, air density of 1.2 kg per m^3 (0.0750 pounds per cubic foot), an air flow constant of 0.84, specific heat of 0.24, cooling surface 20 times the frontal area, and a rise in air temperature of 27.7° C or 50° F in passing through the radiator.

Then, the heat taken up by the air per square meter frontal area of core is $89.4 \times 0.84 \times 1.2 \times 0.24 \times 27.7 = 600$ kilogram calories per second, or per square foot frontal area is $293 \times 0.84 \times 0.0750 \times 0.24 \times 50 = 222$ Btu per second.

Taking the thermal conductivities [38] of copper, brass, aluminum, and iron, respectively, as 0.91, 0.26, 0.49, and 0.14, in $\frac{\text{cal}}{\text{cm} \times \text{sec} \times °\text{C}}$ and computing the temperature difference required to conduct heat at this rate through 20 square meters of metal of various thicknesses, Table 23 is computed.

TABLE 23.—Temperature Drop Through Metal of a Radiator Core under Extreme Conditions (Conditions Stated in Art. 117)

Thickness of metal	Temperature drop through metal				Thickness of metal	Temperature drop through metal			
	Copper	Brass	Aluminum	Iron		Copper	Brass	Aluminum	Iron
cm	°C	°C	°C	°C	Inches	°F	°F	°F	°F
0.01	0.033	0.12	0.06	0.21	0.005	0.075	0.26	0.14	0.49
.02	.07	.23	.12	.43	.010	.15	.53	.28	.98
.03	.10	.35	.18	.64	.015	.23	.79	.43	1.5
.04	.13	.46	.25	.86	.020	.30	1.1	.56	2.0
.05	.16	.58	.31	1.07	025	.37	1.3	.70	2.5
.06	.20	.69	.37	1.3	.030	.45	1.6	.84	2.9
.07	.23	.81	.43	1.5					

APPENDIX E.—CHOICE OF TEMPERATURE DIFFERENCE TO BE USED IN EXPRESSING RESULTS OF HEAT DISSIPATION MEASUREMENTS

118. The comparatively small change in temperature of the water passing through a radiator makes it relatively easy to compute or estimate the effective average temperature under any probable conditions of use. This is not true for the air, and it would be distinctly inconvenient to have data for a given type of core expressed in terms involving the average temperature of the air, because in any use of such data it is only the entrance air temperature which is specified. The average can not, in general, be computed quickly or estimated, because too many factors enter into fixing the exit air temperature. For the intercomparison of radiator cores it is found possible to express the results of measurements conveniently in terms of entrance air temperature and average water temperature without in any way affecting the accuracy of expression of relative magnitudes. The algebraic proof of this follows.

Assume a particular radiator under conditions of constant air flow and water flow but with varying temperatures and consequently varying heat dissipation. It may

[38] Kaye and Laby, Physical and Chemical Constants, p. 51.

also be assumed for work with not too great temperature differences that the heat dissipation is proportional to the difference between the mean water temperature and the arithmetical mean of the temperatures of the air at entrance and exit. This assumption is, of course, not strictly accurate, but is sufficiently close for the kind of work required in radiator tests.

Let H=heat dissipated, in units of power.
T_w=mean temperature of water.
T_1=temperature of air at entrance.
T_2=temperature of air at exit.
$T=T_w-T_1$.
k=a constant.

Also, let accented and unaccented symbols denote, respectively, two sets of values under conditions similar, except that the temperatures may be different in the two cases. The assumption stated above may be expressed in the equation

$$\frac{H'}{H}=\frac{T'_w-\frac{T'_1+T'_2}{2}}{T_w-\frac{T_1+T_2}{2}}. \tag{1}$$

The heat taken up by the air is evidently

$$H=k(T_2-T_1) \tag{2}$$

from which

$$T_2=T_1+\frac{H}{k} \tag{3}$$

and from equation (3) equation (1) may be written

$$\frac{H'}{H}=\frac{T'_w-T'_1-\frac{H'}{2k}}{T_w-T_1-\frac{H}{2k}} \tag{4}$$

from which

$$\frac{H'}{H}=\frac{T'-\frac{H'}{2k}}{T-\frac{H}{2k}}. \tag{5}$$

Now letting

$$\frac{H}{2k}=A$$

$$\frac{H'}{H}=\frac{T'-\frac{H'}{H}A}{T-A} \tag{6}$$

which is true only when

$$\frac{H'}{H}=\frac{T'}{T}. \tag{7}$$

For ordinary purposes and under ordinary conditions of use the difference between the true mean temperature of the water and the arithmetical mean of the temperatures of the water at entrance and exit is so small that the arithmetical mean may be used safely.

APPENDIX F.—DERIVATION OF EQUATION FOR EFFECTIVENESS OF INDIRECT COOLING SURFACE

119. The effectiveness of indirect cooling surface is defined as the ratio of its rate of dissipation of heat to that of an equal area of direct surface under the same conditions of air flow, but at a temperature equal to that of the parts of the indirect surface that are adjacent to its source of heat.

The form of "fin" to be considered is one found in many cellular types of radiator, extending from front face to rear face of the radiator and from one water tube to another. The fins of "fin-and-tube" types present quite a different mathematical problem, and since they are of little importance in aeronautic work will not be considered here.

Two cases of longitudinal fins will be distinguished: (1) Fin in good thermal contact with both water-tube walls, i. e., along both long edges of fin; and (2) fin in good thermal contact with only one water-tube, i. e., along only one edge of fin. Fins of the first class are found in the radiator C–4 and of the second class in many of the square-cell types.

In each case it will be assumed (1) that the depth of the water tube is so nearly equal to the depth of the radiator as to justify neglect of any inequality, (2) that the fin is long in comparison with its width, and (3) that the temperature of the fin does not vary appreciably with depth of the radiator, although decreasing across the width of the fin.

An analysis similar to that of Appendix E would show that if heat dissipation of any element of cooling surface is proportional to the difference in temperature between such an element and the air passing it, the heat dissipation is also proportional to the difference in temperature between the surface and the *entering* air, provided that the temperature distribution be such that the arithmetical mean of entrance and exit air temperatures is a reliable substitute for the mean effective air temperature, properly averaged over the whole surface. The assumption is but a rough approximation to the truth, as indicated by Figs. 123–127, but it is good for the purposes of this article. The conclusions reached would not be altered greatly by the still more sweeping assumption of no appreciable change at all in the air temperature as the air traverses the tubes. For convenience all temperature differences will be referred to entering air, and in the mathematical treatment the temperature scale will be assumed so chosen as to make the temperature of the entering air equal to zero.

120. Case I. Thermal Contact on Both Sides—In accordance with assumptions (1) and (2) the effects of the ends of the fins will be neglected and the problem reduces to the case of a long, thin metal strip with constant temperature at each long edge where the strip is in metallic contact with the water tube. The flow of heat is practically unidimensional from the edges toward the center line of the fin, and if the fin is uniform in thickness and conductivity, and the temperature the same at the two edges, it is clear that no heat will flow across the center line of the fin and the temperature gradient will vanish along that line. Under these conditions the heat dissipated by the fin may be found as follows:

Using any consistent units, let

x=distance measured across the fin, away from one water-tube wall.

b=width of fin (distance between water tubes).

y=thickness of fin.

l=length of fin.

s=cross sectional area of fin over a section normal to the direction of flow of heat.

p=perimeter of the section s.

k=thermal conductivity of the fin.

q=heat dissipated from surface of fin in units of heat per unit time, per unit surface, per unit temperature difference between surface and entering air.

θ=temperature of metal of fin (temperature of entering air assumed zero).

θ_0=temperature of water-tube wall.
Q=total heat dissipation of fin in units of heat per unit time.
E=effectiveness of fin.

Considering a section through the fin at a distance x from one water-tube wall, the heat conducted per unit time through the fin across this section is equal to

$$ks\frac{d\theta}{dx} \tag{1}$$

and the heat conducted past a near-by section at the distance $(x+\triangle x)$ from the wall is

$$ks\left(\frac{d\theta}{dx}+\frac{d^2\theta}{dx^2}\triangle x\right). \tag{2}$$

The heat dissipated from the surface between these sections is the difference between (1) and (2), or

$$ks\left(\frac{d^2\theta}{dx^2}\right)\triangle x \tag{3}$$

and is also equal to

$$q\theta p\triangle x. \tag{4}$$

Equating (3) and (4) and letting

$$\alpha=\sqrt{\frac{qp}{ks}} \tag{5}$$

gives

$$\frac{d^2\theta}{dx^2}=\alpha^2\theta. \tag{6}$$

A solution of this equation may be put in the form

$$\theta=A\cosh(\alpha x-B) \tag{7}$$

where A and B are constants which may be evaluated from the boundary conditions

$$\theta=\theta_0 \text{ when } x=O$$

$$\frac{d\theta}{dx}=O \text{ when } x=\frac{b}{2} \tag{8}$$

These constants are found to be

$$B=\alpha\frac{b}{2} \tag{9}$$

$$A=\frac{\theta_0}{\cosh\alpha\frac{b}{2}} \tag{10}$$

The heat dissipated per unit time by the whole fin is given by

$$Q=2\int_0^{\frac{b}{2}}q\theta p\,dx \tag{11}$$

$$Q=2qpA\int_0^{\frac{b}{2}}\cosh(\alpha x-B)\,dx$$

$$=\frac{2qpA}{\alpha}\left[\sinh(\alpha x-B)\right]_0^{\frac{b}{2}}$$

$$=\frac{2qp\theta_0}{\alpha}\frac{\sinh\alpha\frac{b}{2}}{\cosh\alpha\frac{b}{2}}=\frac{2qp\theta_0}{\alpha}\tanh\alpha\frac{b}{2} \tag{12}$$

Now, the average heat dissipation for the fin per unit time, per unit surface, per unit temperature difference between water-tube wall and entering air is

$$\frac{Q}{bp\theta_0} \tag{13}$$

and the effectiveness of the fin is by definition the ratio of this quantity to the rate, q, of dissipation per unit area of water-tube wall.

$$E=\frac{Q}{bp\theta_0 q}=\frac{2qp\theta_0}{bp\theta_0 q\alpha}\tanh \alpha\frac{b}{2} \tag{14}$$

$$=\frac{\tanh \alpha\frac{b}{2}}{\alpha\frac{b}{2}} \tag{15}$$

or letting

$$u_1=\alpha\frac{b}{2}=\frac{b}{2}\sqrt{\frac{pq}{ks}} \tag{16}$$

$$E=\frac{\tanh u_1}{u_1} \tag{17}$$

Since the perimeter p is practically equal to twice the length of the fin, the equation for α may be put in slightly more convenient form by means of the substitution

$$\frac{p}{s}=\frac{2l}{yl}=\frac{2}{y} \tag{18}$$

and the value of u_1 may be put in the form

$$u_1=\frac{\alpha b}{2}=\frac{b}{2}\sqrt{\frac{2q}{yk}} \tag{19}$$

121. Case II. Thermal Contact on One Side Only.—If the fin is in good thermal contact with the water-tube walls along only one edge, a very good approximation may be made by neglecting the heat dissipated from the free edge, since the thickness of the fin is seldom greater than 2 per cent of its width. In this case the derivation is changed in the following respects:

(1) The conditions (8) become

$$\theta=\theta_0 \text{ when } x=O$$

$$\frac{d\theta}{dx}=O \text{ when } x=b, \tag{8'}$$

(2) B becomes (αb),

(3) equation (11) becomes,

$$Q=\int_0^b q\theta p dx, \tag{10'}$$

which integrates to

$$Q=\frac{qp\theta_0}{\alpha}\tanh \alpha b, \tag{12'}$$

(4) the effectiveness becomes

$$E=\frac{\tanh \alpha b}{\alpha b}, \tag{15'}$$

which, letting

$$u_2=\alpha b=b\sqrt{\frac{2q}{yk}} \tag{16'}$$

becomes

$$E=\frac{\tanh u_2}{u_2}. \tag{17'}$$

APPENDIX G.—EXPERIMENTAL DATA

122. In this appendix are collected the laboratory data upon which are based the conclusions forming the body of this paper. Data which have been incorporated explicitly into the material of the foregoing pages are not repeated in the following tables and graphs, but are cross referenced, as, for example, in Table 30. To reproduce log sheets of the laboratory work would require a volume many times as thick as this, and, in general, it will be noted that the material given is condensed to a single line for each experimental run in the laboratory.

After this paper was prepared for publication it developed that the funds available for printing would not permit of the publication of this appendix, the tables for which are therefore given by title. The reader who is interested in reviewing the vast amount of experimental laboratory data upon which conclusions in this paper are based may do so by consulting the original manuscript at the Bureau of Standards. The elimination of these data from the present paper is regretted, but there seems to be no other alternative, since the appropriation allotted to the Bureau for printing falls considerably short of that required to publish its scientific and technical work. If funds should become available in the near future, and there appears to be a demand for it, the appendixes to the present paper may then be published separately as a supplement.

Table 24. Summary of Data Obtained in Heat Dissipation Measurements. Measurements made in closed or "steam" tunnel using steam as source of heat for 64 cores, and using hot water as the source of heat for 12 cores.

Table 25. Summary of Heat Dissipation Data Obtained in Reduced Pressure Tunnel.

Table 26. Air Flow Data—Venturi Meter.

Table 27. Air Flow Data for Radiator in Nose of Model Fuselage.

Table 28. Air Flow and Air Flow Distribution in Streamlined Radiator.

Table 29. Observed Data for Study of Surface Friction in a Single Long Tube.

Table 30. Head Resistance Data.

Table 31. Head Resistance of Cores Yawed at Various Angles.

Much data given graphically will be found on pages 409–426.

APPENDIX H.—BIBLIOGRAPHY

Since a complete bibliography of subjects allied even most intimately with the subject matter of this paper would be a compendium of dictionary size, it has been difficult to choose a suitable limitation to listing. The authors have concluded that the interests of the reader would be served best by indicating the few papers which have proven of greatest value in their relation to the work. Specific reference to a number of these will be found scattered through footnotes in the several sections of the paper.

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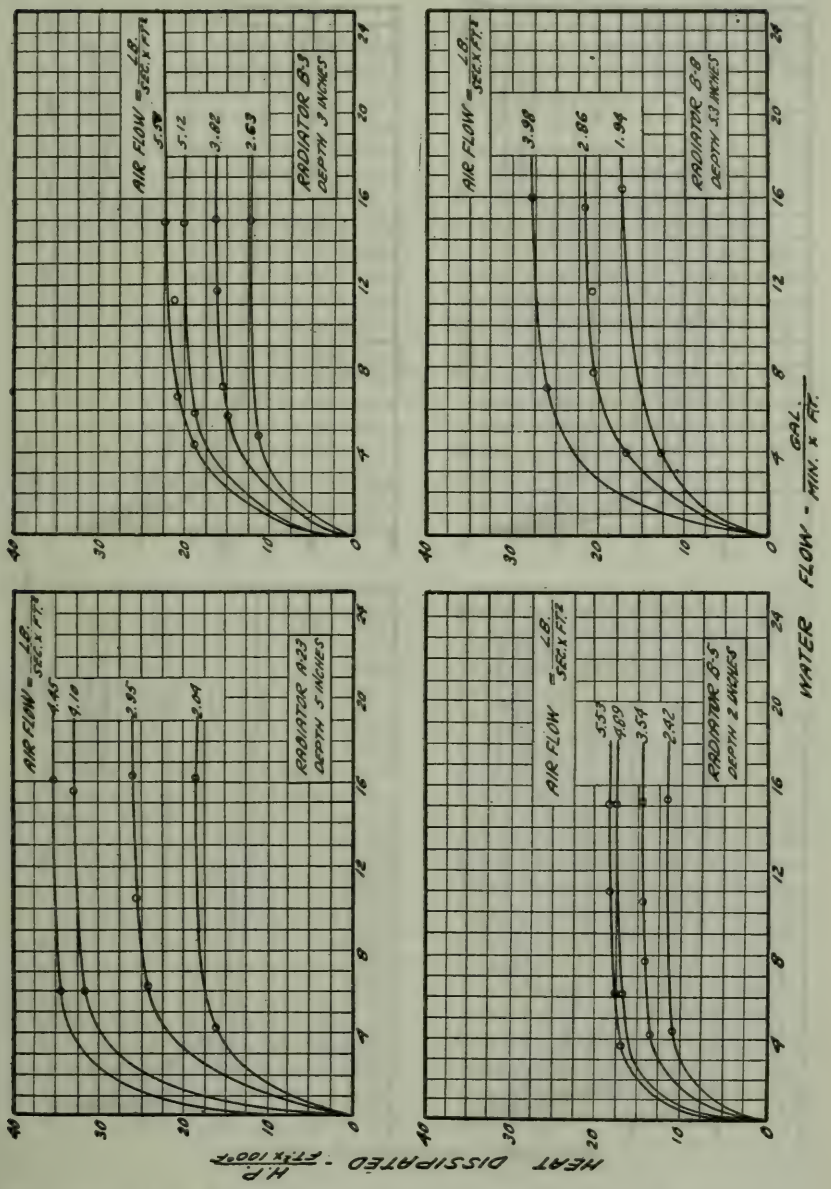
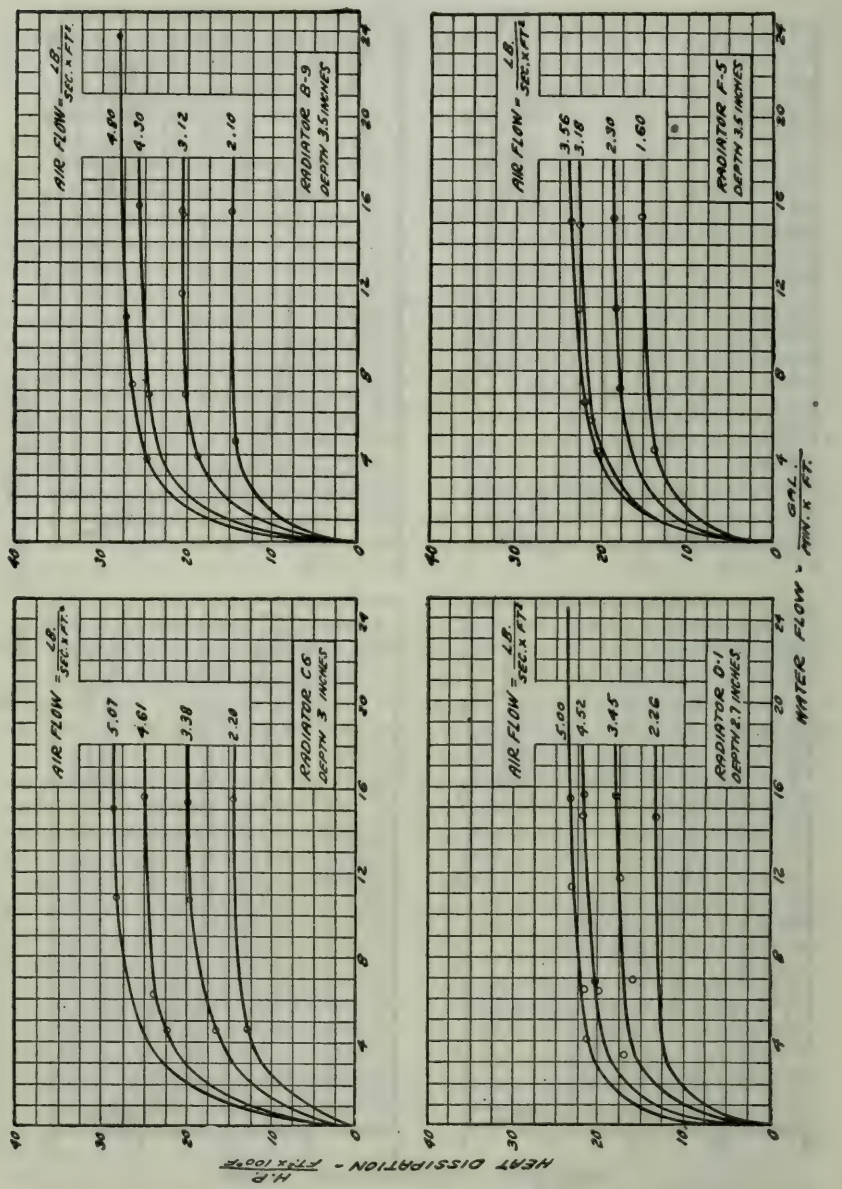


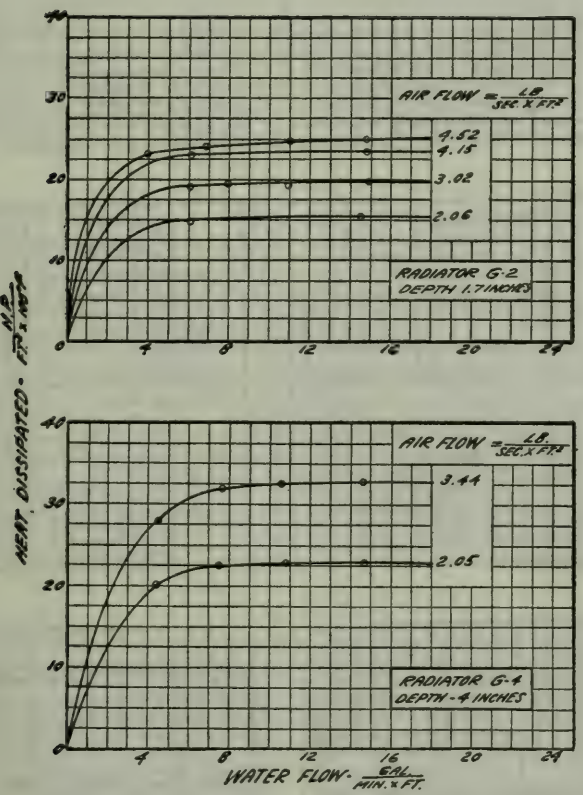
FIGS. 128–31.—*Heat dissipation as a function of rate of water flow in a radiator core*

Data from which the figures were drawn will be found in Table 25, under the respective core listings A–23, B–3, B–5, B–8. Conclusions drawn from the curves are discussed in Art. 56, Table 10.



FIGS. 132–135.—*Heat dissipation as a function of rate of water flow in a radiator core*

Data from which the figures were drawn will be found in Table 25, under the respective core listings B–9, C–6, D–1, F–5. Conclusions drawn from the curves are discussed in Art. 56, Table 10.



FIGS. 136–137.—*Heat dissipation as a function of rate of water flow in a radiator core*

Data from which the figures were drawn will be found in Table 25, under the respective core listings G–2, G–4. Conclusions drawn from the curves are discussed in Art. 56, Table 10

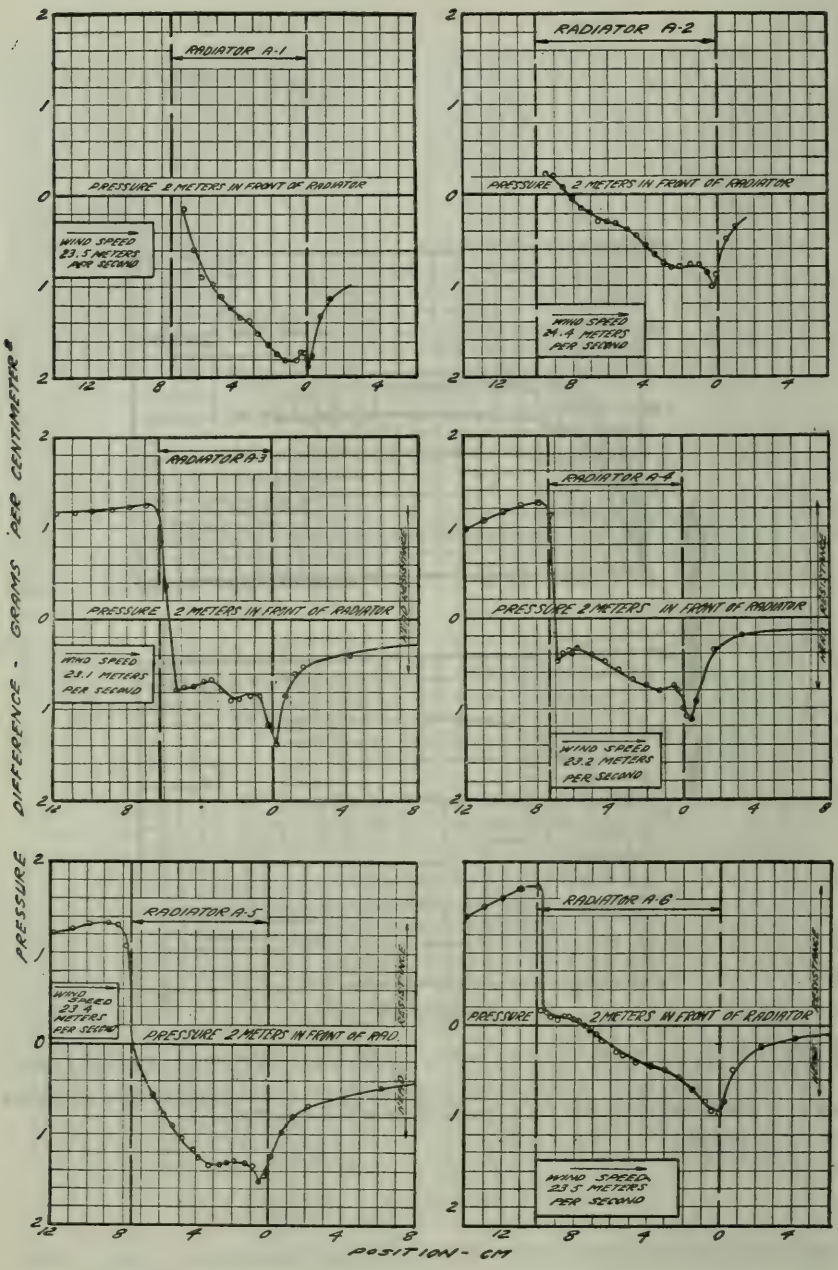


FIG. 138.—*Air flow data for six square cell cores (A–1 to A–6)*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

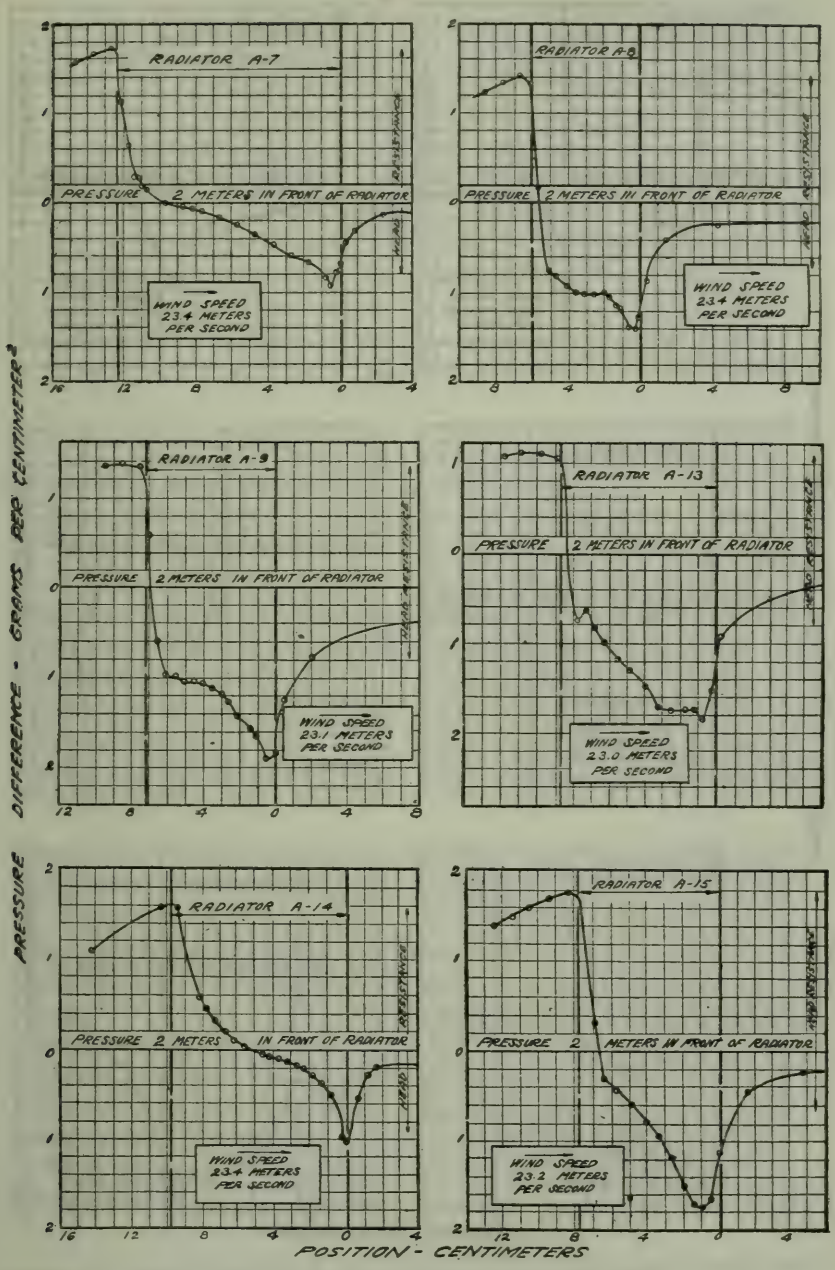


FIG. 139.—*Air flow data for six square cell cores (A–7, 8, 9, 13, 14, 15)*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

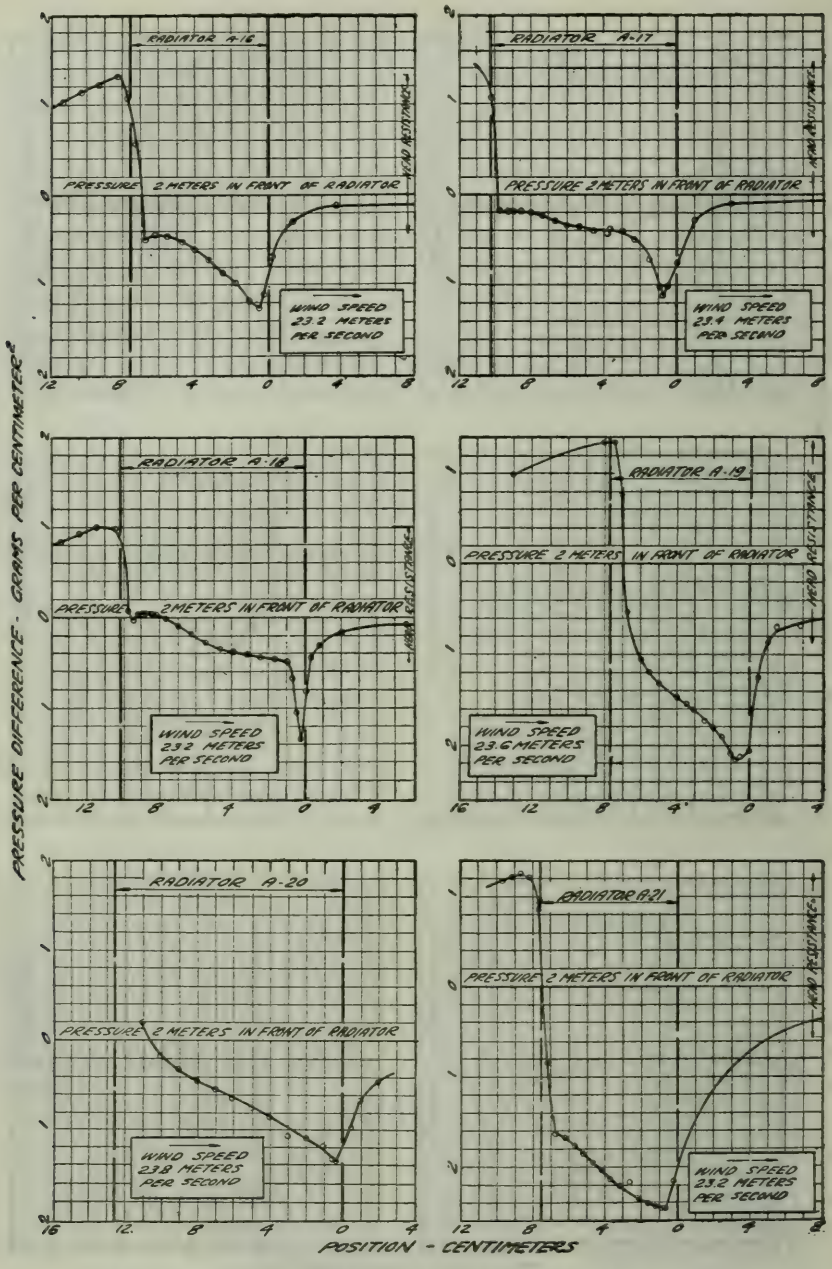


FIG. 140.—*Air flow data for six cellular cores (A–16 to A–21) with air tubes of rectangular (nearly square) cross section*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

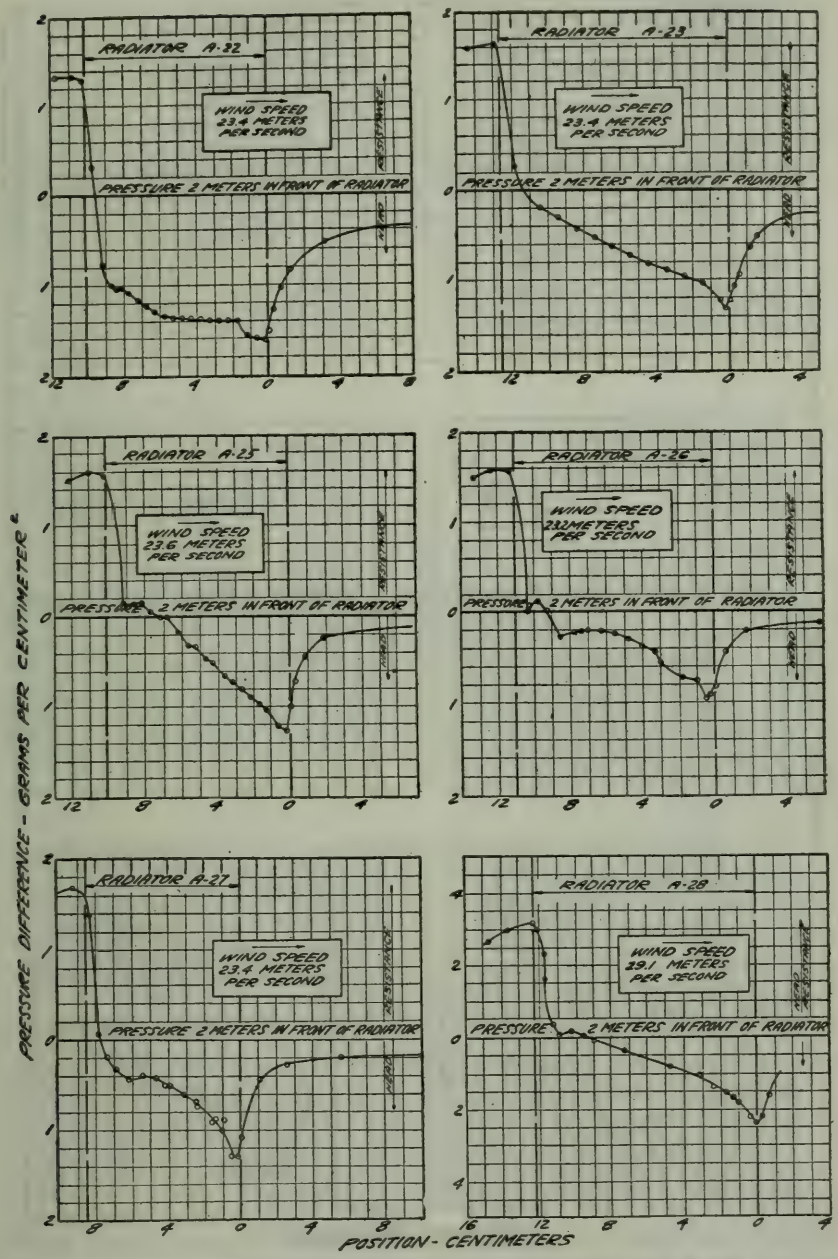


FIG. 141.—*Air flow data for six square cell cores (A–22 to A–28)*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

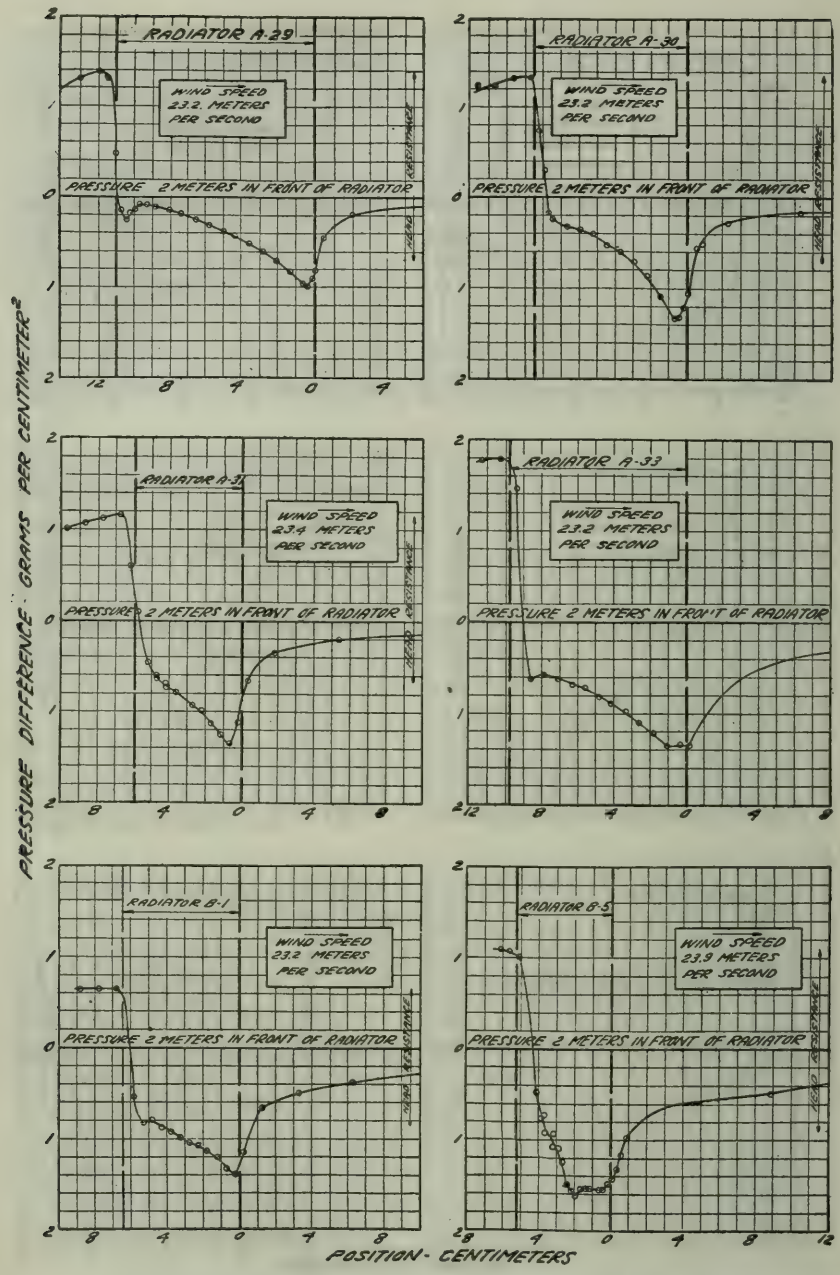


FIG. 142.—*Air flow data for four square cell cores (A–29 to A–33) and two hexagonal cell cores (B–1, B–5), the first of simple type and the second with a lattice of turbulence vanes*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

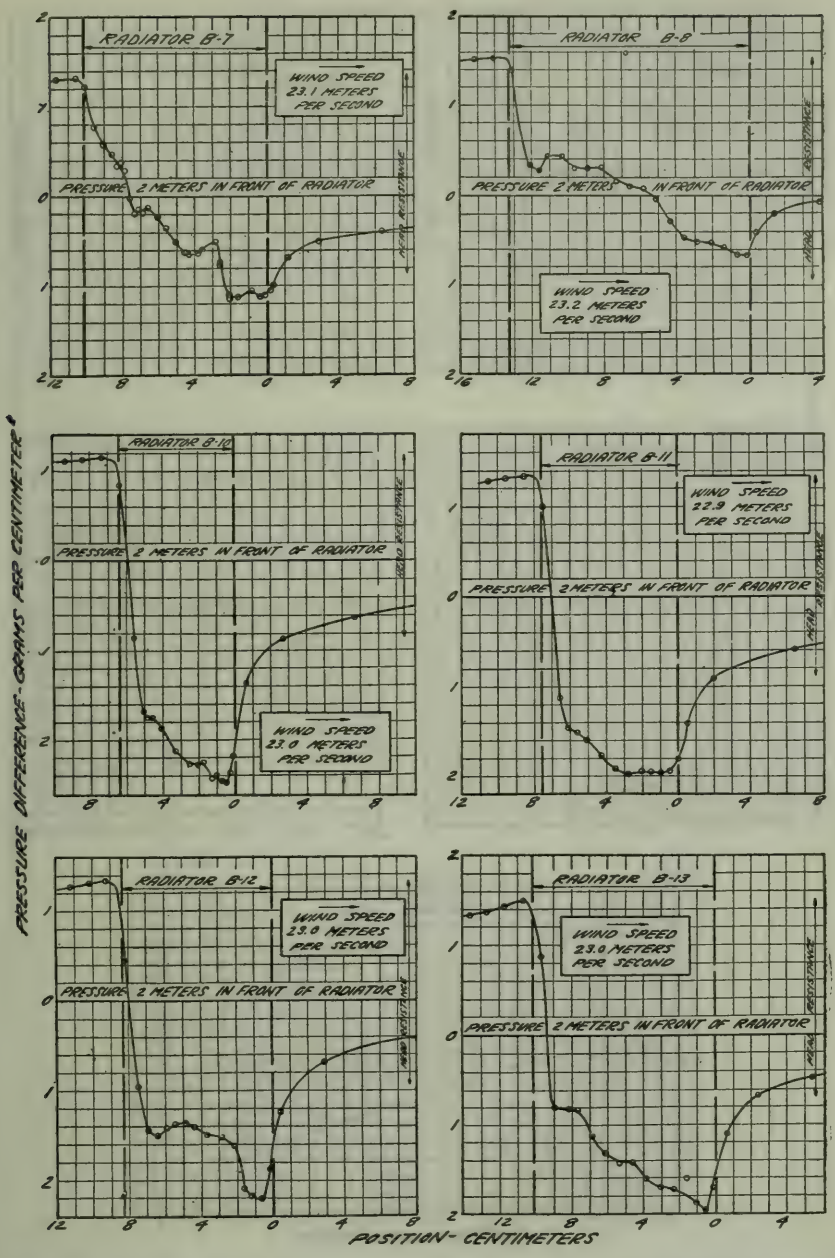


FIG. 143.—*Air flow data for six hexagonal cell cores (B–7 to B–13), the air tube walls being latticed or provided with turbulence vanes*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

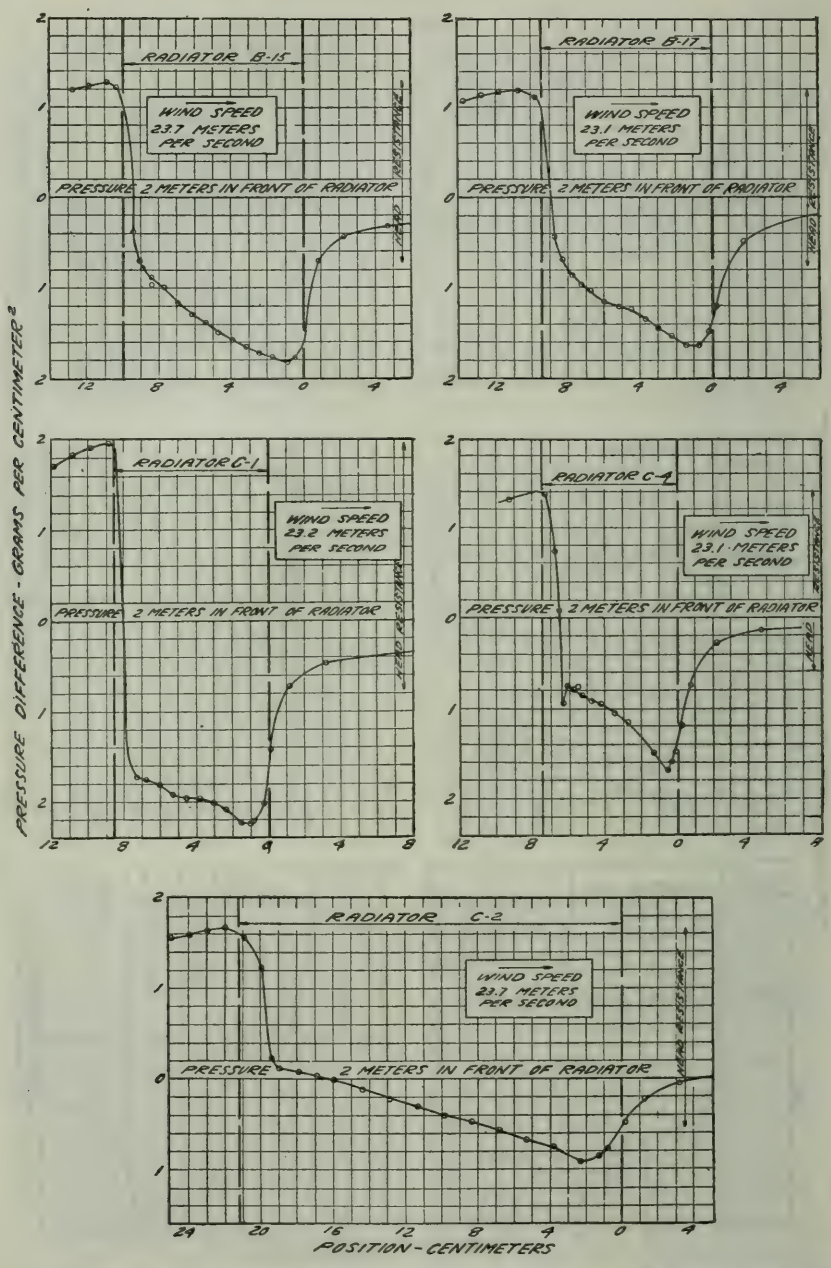


FIG. 144.—*Air flow data for two hexagonal cell cores (B–15, B–17) of simple type without any turbulence vanes or other distorting elements, and of three other cellular cores (C–1, C–4, C–2) of irregular form, illustrated in Figs. 88, 91, 89. C–2 has plain circular air tubes and it will be noted that the pressure gradient curve is very smooth and regular*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

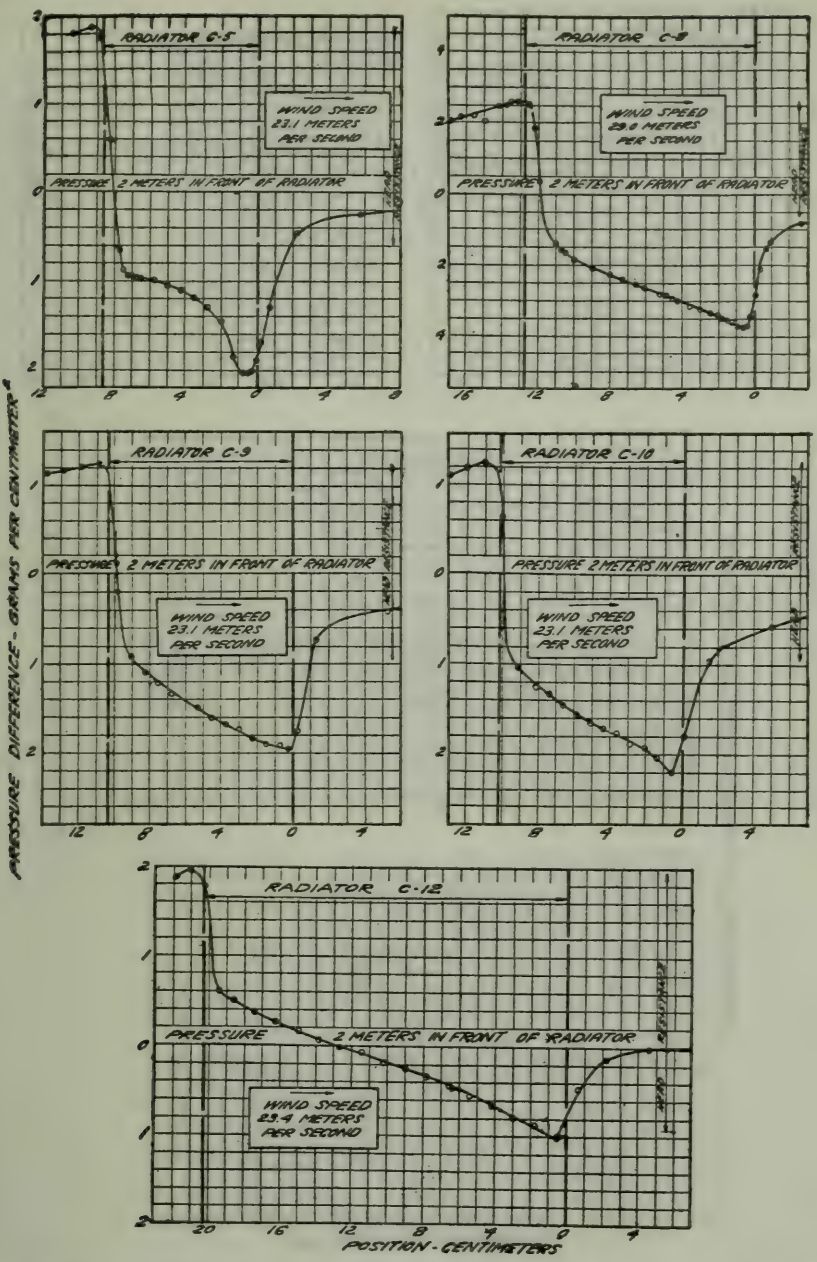


FIG. 145.—*Air flow data for five circular cell cores. C–5 is of peculiar construction illustrated in Fig. 92. Air flow in the smooth circular tubes is modified by the entrance condition incident to having the "cushion" shaped cell adjacent to it. C–8 to C–12 are circular tube cores with the ends of the air tubes pressed into hexagons for joining together*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

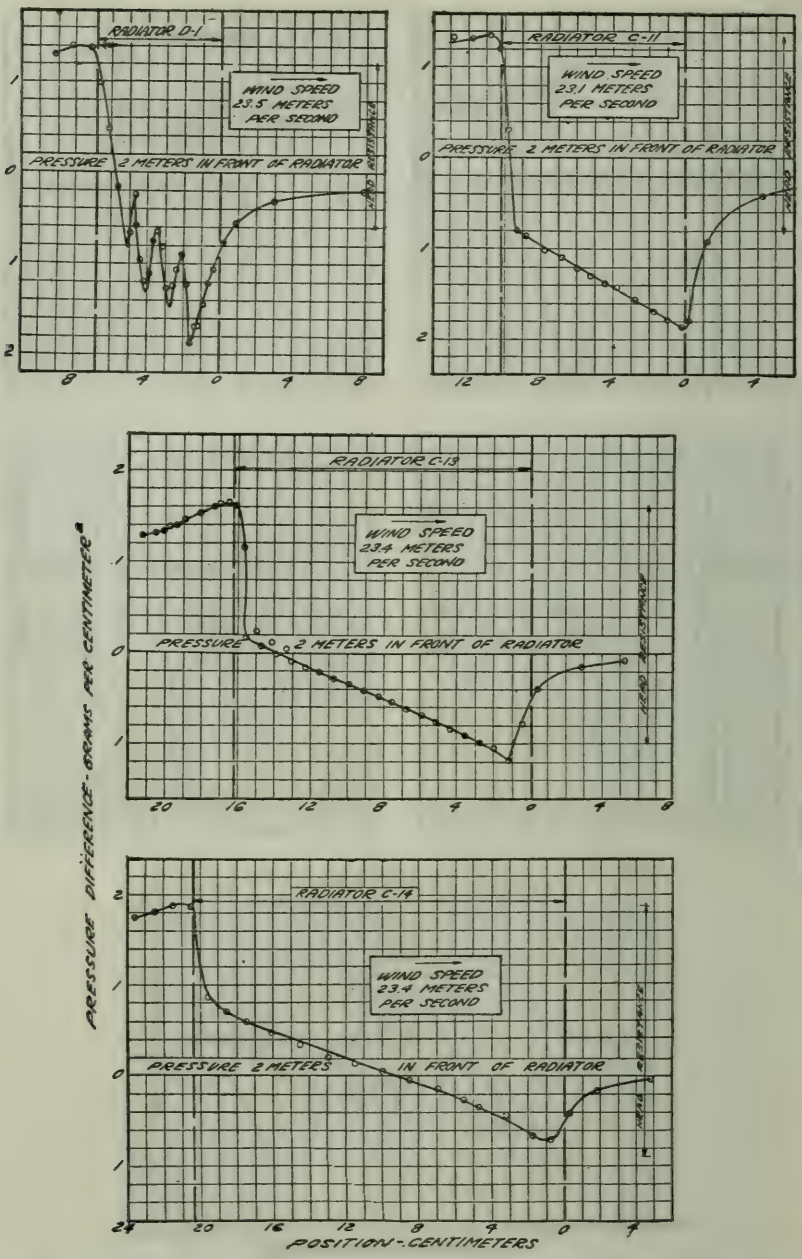


FIG. 146.—*Air flow data for three circular cell cores (C–11, 13, 14) in which the circular tubes are pressed to hexagons at the ends, and for an irregular core of construction shown in Figs. 102 and 103. The oscillating character of the pressure gradient curve is due to the dimples shown in Fig. 103*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

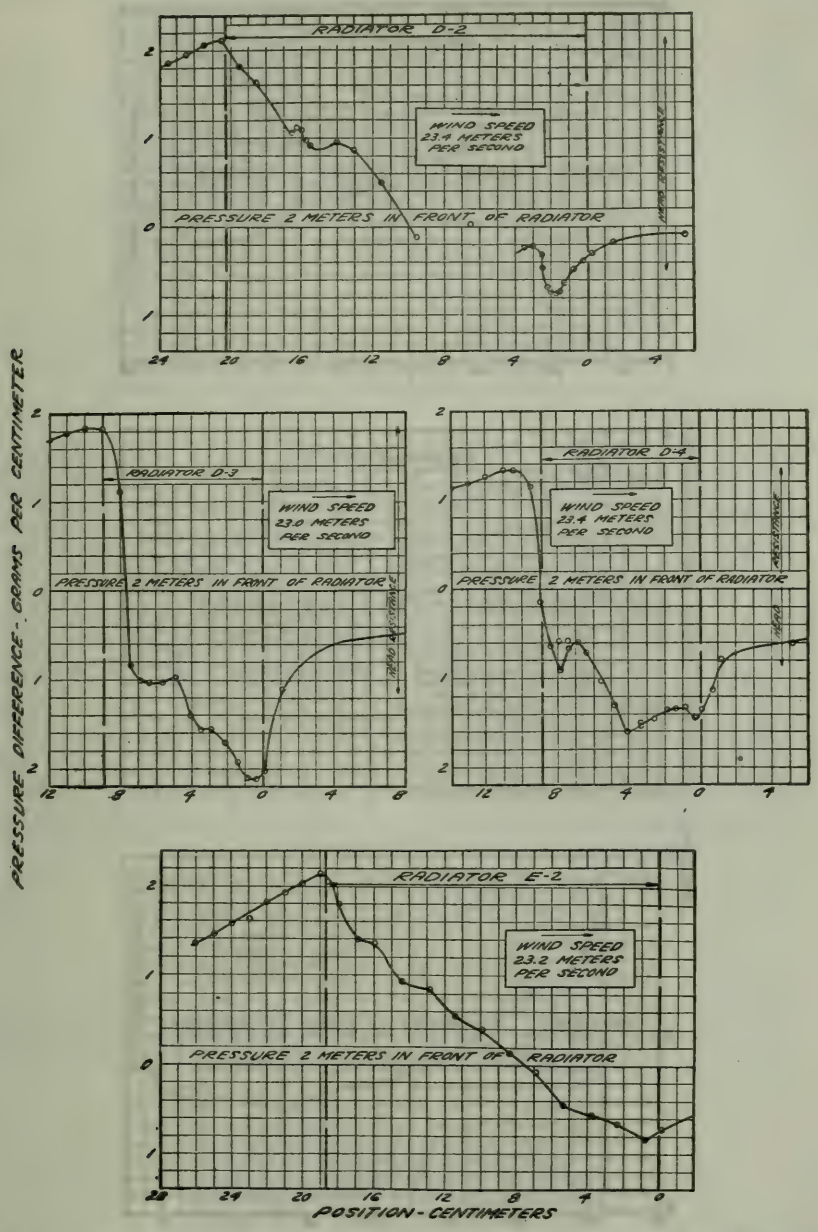


FIG. 147.—*Air flow data for miscellaneous cores of construction shown in the heading of Table 20 (p. 368). E–2 is a flat plate core with perforated water tubes giving irregularities in the air flow*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

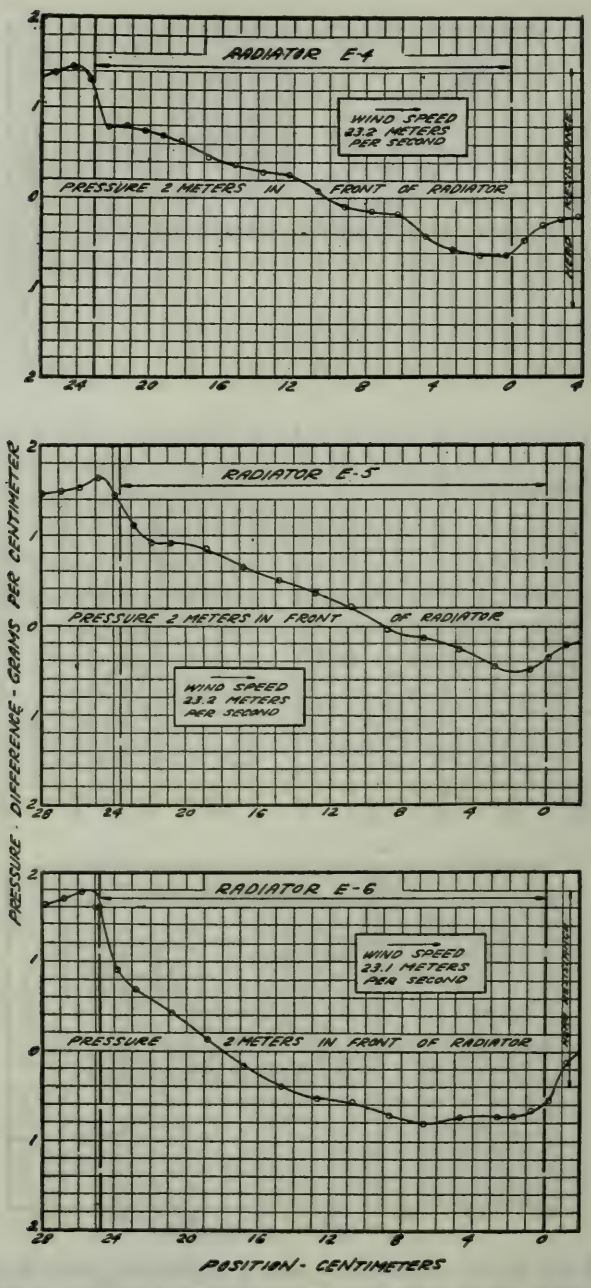


FIG. 148.—*Air flow data for two perforated plate cores (E–4, E–5) and flat plate core E–6*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

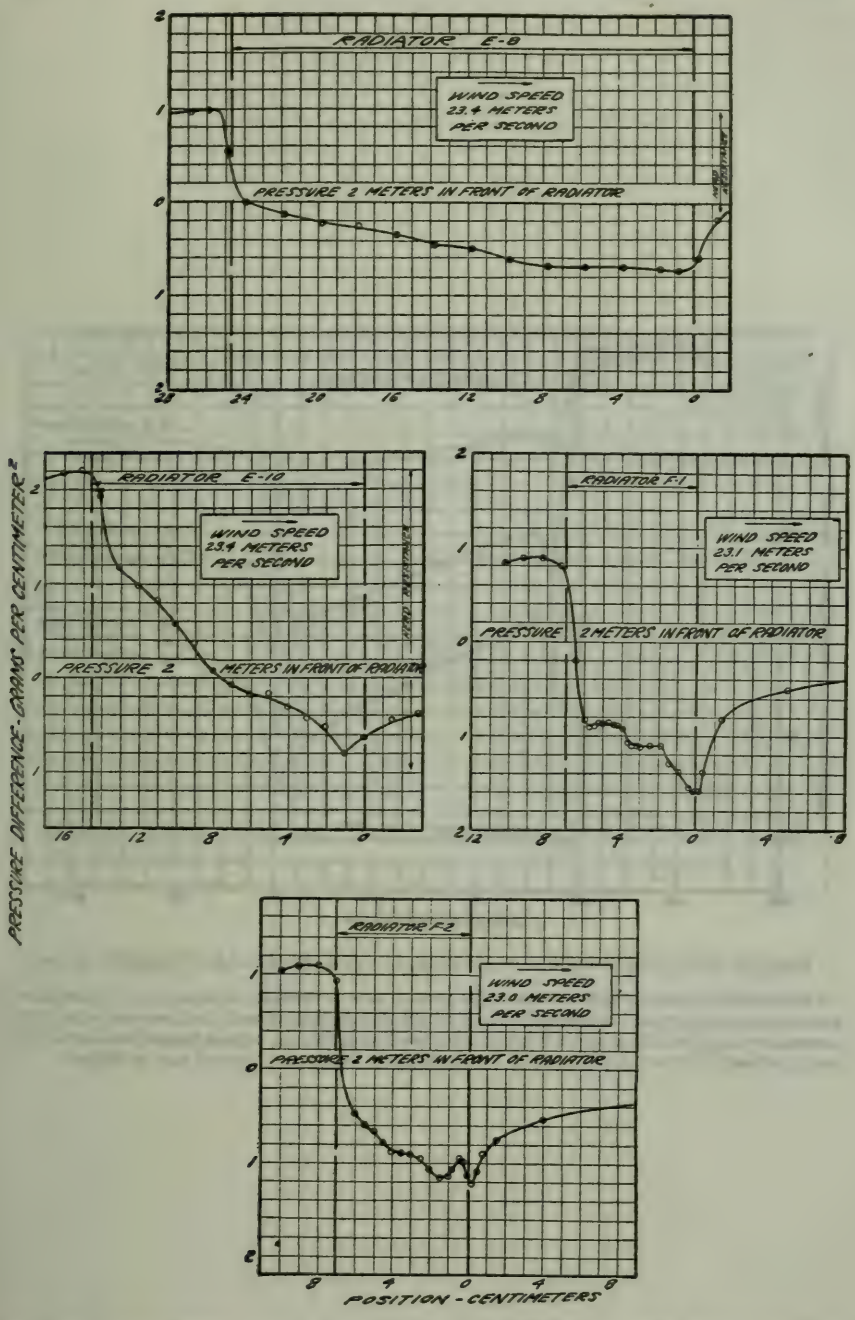


FIG. 149.—*Air flow data for flat plate core E–8, corrugated plate core E–10, and two fin and tube cores (F–1, F–2)*

By mapping the pressure gradient in the air tubes as described in Arts. 15–17, the rate of air flow was determined. The graphic record of original observations is reproduced in lieu of tabulating the data. The wind speed is that in the large "open" wind tunnel some distance in front of the radiator

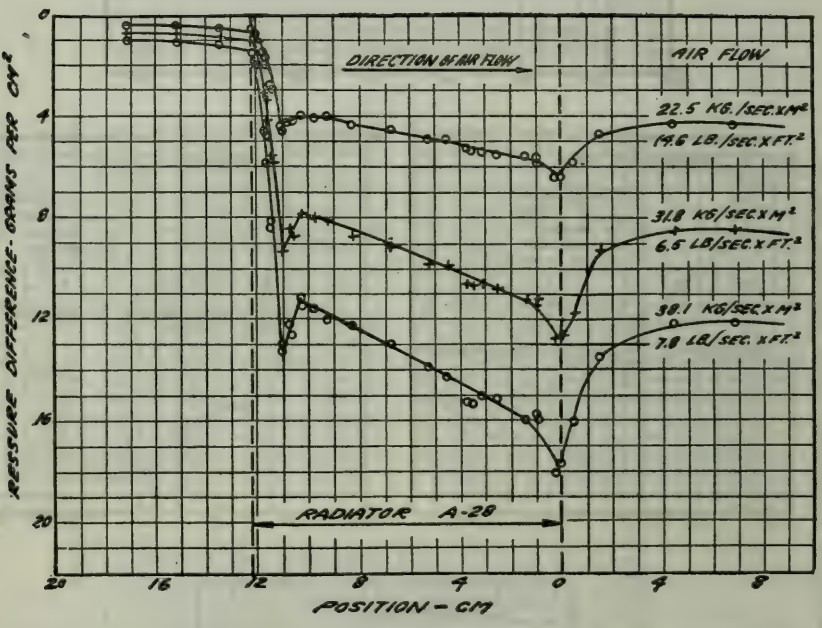


FIG. 150.—*Air flow data for core A–28 (square cell) in closed (or "steam") tunnel*

This figure illustrates the method of using the pressure tube as described in Arts. 15–17. Three rates of air flow, measured by the pitot grid in the closed tunnel, give the calibration of the "pressure tube" in this core and by comparing the pressure drop curve for core A–28 in Fig. 141 with an interpolated curve of the family defined by the above three curves, a computation of the air flow constant may be effected

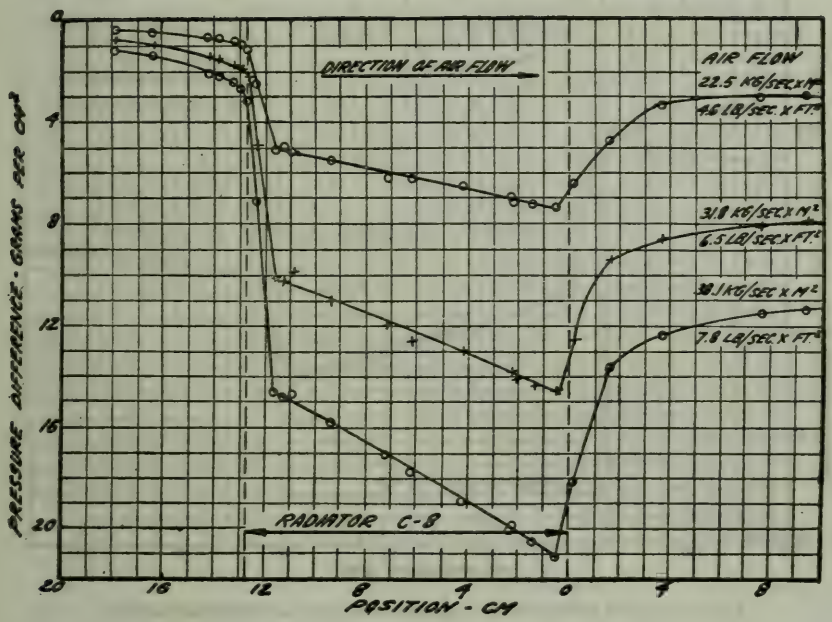


FIG. 151.—*Air flow data for a circular cell core in the closed (or "steam") tunnel*

Data used exactly as described above for Fig. 150. The figure is introduced to show how very regular is the pressure drop through a simple cylindrical air tube. Curves of this same nature, at three or more rates of air flow, were required for each core, being combined with Figs. 138–149 to evaluate the air flow constants

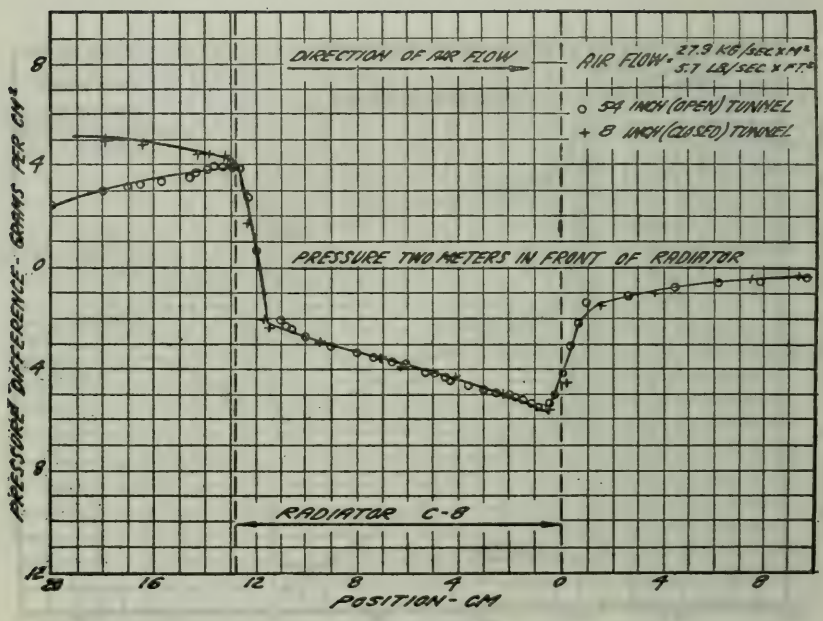


FIG. 152.—*Air flow data for a circular cell core in both wind tunnels*

A laboratory interpolation of curves usually interpolated by graphic or analytic means. Having mapped pressure gradient in the closed tunnel for a given air flow, the core was mounted in the open tunnel and the wind speed adjusted to give the same pressure drop at some point, and as the curves show this means coincidence at all points (except immediately in front of core). This procedure furnished an excellent test of the validity of the assumptions on which air-flow-constant determinations were made.

WASHINGTON, June 21, 1921.

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DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 212

[Part of Vol. 16]

CARBON MONOXIDE IN THE PRODUCTS OF COMBUSTION FROM NATURAL GAS BURNERS

BY

I. V. BRUMBAUGH, Associate Gas Engineer

Bureau of Standards

and

G. W. JONES, Assistant Chemist

Bureau of Mines

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BUREAU OF STANDARDS

CARBON MONOXIDE IN THE PRODUCTS OF COMBUSTION FROM NATURAL GAS BURNERS

By I. V. Brumbaugh and G. W. Jones

ABSTRACT

Many natural-gas appliances are notoriously inefficient. Solid top stoves with low set burners and grid top stoves with low set burners consume two to eight times as much gas as stoves with raised burners and grid tops. On account of the liberation of carbon monoxide, a poisonous gas, with the products of combustion when the flame is improperly aerated it is not practical to place burners at the distance from utensils where the maximum efficiency is obtained. Burners of the "star" type should be placed about 1 inch, the "slot" burner about ¾ inch, and the "disc" type about 1¼ inches from utensil.

From the many tests for carbon monoxide made with five different burners and different types of flames at rates of consumption of 6.0 and 8.0 cubic feet per hour (6480 and 8640 Btu per hour), the maximum rate of liberation of carbon monoxide was found to be 0.25 cubic foot per hour and was obtained with a very soft flame and a close position of utensil which caused the flame to "float" and extend up the side of utensil. It is not a dangerous rate unless one works directly over the burner, or several burners are in use at the same time for several hours, or the room is unventilated.

No carbon monoxide was found where the blue inner cone of the flame was not allowed to touch the utensil. A yellow flame will produce carbon monoxide at a rate much greater than a blue flame when the utensil is so close to the burner as to cause a floating flame.

A natural gas flame was found to be smothered from deficiency of oxygen when the content of the atmosphere had been diminished to about 15.5 per cent. When one considers the natural ventilation which takes place through the windows and doors it would seem that the danger from carbon monoxide poisoning with natural gas top burners is quite remote.

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I. INTRODUCTION

Carbon monoxide, a very poisonous gas, is produced in combustion processes where there is a deficiency of oxygen for completely burning the carbon in the gas to carbon dioxide. A condition favorable for the production of carbon monoxide results with the usual type of gas burner when the flame is insufficiently aerated by placing the burner too close to the utensil.

The efficiency of natural gas burners is greatly increased by placing the burner close to the utensil. It is therefore very important to know how close the burner can be placed to the utensil without producing dangerous quantities of carbon monoxide. The air shutter adjustment of the burner which determines the characteristic of the flame has also much to do with securing good combustion.

We know of no tests that have been made of the amount of carbon monoxide that can be liberated from the different types of domestic burners when operated with different flame characteristics, different rates of consumption of natural gas, and different positions of burner from utensil. It was therefore considered of great importance to investigate this matter very thoroughly.

The tests reported in this paper were made in connection with the investigation conducted by the Bureau of Standards on the design and efficiency of natural gas burners. The tests were made in the Bureau of Mines gas laboratory in Pittsburgh. This laboratory was splendidly equipped to make the gas analyses, and it was agreed between the Bureau of Standards and the Bureau of Mines to investigate and report jointly this phase of the problem.

Three different types of domestic gas burners as commonly used were tested under a variety of conditions of operation, with especial reference to conditions where carbon monoxide would be most likely produced.

The products of combustion were analyzed for the amount of carbon monoxide, carbon dioxide, oxygen, and nitrogen. Under some conditions very small amounts of partly oxidized products, as aldehydes, were known to be present, but in proportions too small to be tested by the usual methods of analysis.

Special acknowledgment is made to W. L. Parker, assistant chemist, Bureau of Mines, for the painstaking manner in which he made the analyses of the products of combustion here reported. J. H. Eiseman and G. B. Shawn, laboratory assistants, Bureau of Standards, assisted in making the burner tests.

II. CARBON MONOXIDE

Carbon monoxide is a colorless and odorless gas slightly lighter than air, specific gravity 0.967 (air = 1.0), and burns with a pale blue flame. It is one of the combustible constituents of water gas, coal gas, and producer gas. The gas is very poisonous, and it is due to this that so many deaths are caused annually by the accidental or intentional inhaling of artificial gases.

Owing to the fact that carbon monoxide is colorless, odorless, tasteless, and not easily detected by the ordinary senses, it can be present in very dangerous proportions before being detected.

1. ACTION OF CARBON MONOXIDE

Carbon monoxide combines with the hemoglobin of the blood and temporarily destroys its function as an oxygen carrier. After continued exposure a large part of the hemoglobin becomes inactive, depending on the concentration of carbon monoxide present in the atmosphere. The affinity of carbon monoxide for hemoglobin is 250 to 300 times as great as oxygen, and it is easily seen why a small percentage of carbon monoxide soon becomes very dangerous to health when inhaled for some time.

Haldane[1] makes the following statement:

> The poisonous action of carbon monoxide is due to the fact that this gas combines with hemoglobin, the colored blood constituent which normally carries oxygen to the tissues. As the carbon monoxide takes the place of oxygen the blood is more or less prevented from carrying oxygen, and the animal dies, if the process has gone far enough, from want of oxygen. The extent to which the hemoglobin becomes saturated with carbon monoxide depends in the long run on the relative mass influences of the oxygen and carbon monoxide present in the blood as it leaves the lungs.

When the person is removed to an atmosphere free from carbon monoxide, the oxygen of the air displaces the carbon monoxide taken up by the blood. The action, however, is slow.

2. SYMPTOMS OF CARBON MONOXIDE POISONING

The symptoms of carbon monoxide poisoning are described by R. R. Sayers [2] and H. R. O'Brien,[3] who state that:[4]

> The victim of acute carbon monoxide poisoning usually experiences the following symptoms: A tight-stretched-skin feeling across the forehead; a frontal headache, dull and intermittent at first, later more severe and continuous; this headache is replaced or masked by a typical one at the base and back of the skull, which causes the sufferer to hold his head as far back as possible in an effort to obtain relief; dizzi-

[1] Haldane, J. S., Methods of air analysis, p. 109; 1912.
[2] Chief surgeon, U. S. Bureau of Mines.
[3] Car surgeon, U. S. Bureau of Mines.
[4] Forthcoming technical paper on "The treatment of carbon monoxide poisoning."

ness, nausea (feeling of sickness), and lassitude also occur. The pulse is at first normal, but later becomes full and rapid, the skin is flushed, the respiration becomes more rapid with exposure to the gas and later irregular. If the exposure is sufficiently long or the concentration sufficiently great, confusion, convulsions, and unconsciousness develop. As the victim recovers, he remains weak for some time; this is especially true of the muscles of his legs. The headache persists and may be extremely severe. The nausea may be sufficient to produce vomiting. All the symptoms are accentuated by exercise. When a man is overcome by large concentrations the symptoms follow each other rapidly and he may quickly fall unconscious. The rate at which a man is overcome and the sequence in which the symptoms appear depend on several factors: The concentration of the gas, the extent to which he is exerting himself, the state of his health and individual predisposition, and the temperature, humidity, and air movement to which he is exposed. Exercise, high temperature, and great humidity, with no air movement, tend to increase respiration and heart rate, and consequently result in more rapid absorption of carbon monoxide.

As to the quantity of carbon monoxide which may be present before symptoms develop, Haldane [5] states that an addition of 0.05 per cent of carbon monoxide in pure air is just sufficient to produce in time slight symptoms in man. In another experiment Haldane breathed air containing 0.027 per cent of carbon monoxide for 3½ hours. No symptoms were apparent, except perhaps unusual shortness of breath and palpitation of the heart on running up stairs.

Of the more recent authorities on the effect of carbon monoxide on man, Henderson [6] and others found that 0.06 per cent of carbon monoxide in air frequently gave headaches and other symptoms when the subjects were at rest and exposed for one hour. Since carbon monoxide symptoms not only depend upon the concentration of the carbon monoxide present in the atmosphere but also upon the time of exposure, the rate of breathing, or, in other words, the amount of work or exercise being done, and the physical state of the subject, a definite stated concentration of carbon monoxide in air above which symptoms develop can not be given which will apply for all cases. Henderson [6] and others state:

> The whole matter may be even more simply summed up in a single expression involving the time measured in hours, the concentration of carbon monoxide in air in parts per ten thousand and a constant for each degree of physiological effect. The physiological effect of all concentration and times (within reasonable limits) may be defined as follows:
>
> (1) Time×concentration=3, no perceptible effect.
> (2) Time×concentration=6, a just perceptible effect.
> (3) Time×concentration=9, headache and nausea.
> (4) Time×concentration=15, dangerous.
>
> Physical exertion and increased breathing would reduce the constant in the first equation from three to two, one, or even less; and would affect the other equations correspondingly.

[5] Haldane, J. S., The action of carbon monoxide on man, J. Phys., 18, p. 430; 1895.

[6] Henderson, Yandell, Haggard, H. W., Teague, M. C., Pierce, A. Wunderlich, Report of tunnel gas investigation, problem No. 2. Forthcoming publication of the Bureau of Mines.

From the above, the maximum percentage of carbon monoxide allowable for continuous exposure from a hygienic standpoint should not be greater than 0.02 per cent, and for intermittent exposures of 1 hour not greater than 0.04 per cent.

III. EFFECTS OF CARBON DIOXIDE

As regards the amount of carbon dioxide present that may give rise to symptoms of poisoning, Haldane and Smith [7] found that these symptoms do not appear until 3 to 4 per cent of the gas is present, when the breathing becomes slightly affected. Working under these conditions men become quickly fatigued. The symptoms are more marked as the percentage of carbon dioxide is increased, until at 12 to 15 per cent the patient soon becomes unconscious.

More recent information on the action of carbon dioxide on men, experiments performed at the Bureau of Mines by Dr. R. R. Sayers,[8] is of interest. Quoting Dr. Sayers from his report:

> The effect of breathing 0.5 per cent of carbon dioxide in air, according to Hill, is a slight and unnoticeable increase in the ventilation [9] of the lungs and a little more carbon dioxide is produced in the muscles; 2 per cent increases the ventilation of the lungs about 50 per cent; 3 per cent, about 100 per cent; and 5 per cent, about 300 per cent; while 10 per cent can not be endured for more than a minute or so. The effects are headache, sweating, dimness of vision, and tremor. In some experiments carried out at the Bureau of Mines experiment station, Pittsburgh, Pa., it was found that about 2 per cent of carbon dioxide in oxygen produced a slight increase in lung ventilation, but no subjective symptoms; 5 per cent in oxygen caused an increase in lung ventilation of about 100 per cent, but no other signs or symptoms; 7.2 per cent produced 200 per cent increase in lung ventilation and moderate sweating, and a slight fullness in the head was experienced after breathing the mixture for 10 minutes; 9 to 10 per cent produced about 300 per cent increase in lung ventiliaton, and the subject complained of frontal headache and was dizzy and sweating at the end of 10 minutes. About 9 per cent of carbon dioxide in oxygen was breathed by some of the subjects for as long as 45 minutes, but the breathing was very laborious, and dizziness, headache, and sweating were marked. In view of this data, we can conclude that, while it is possible to breathe 9 or 10 per cent of carbon dioxide in oxygen, a percentage above 5 per cent will cause noticeable effects

The above experiments made by the Bureau of Mines were conducted with carbon dioxide and oxygen mixtures; for carbon dioxide and air mixtures the value should be as low or lower than those for carbon dioxide and oxygen mixtures. In other words, if 4 per cent is taken as the maximum amount of carbon dioxide that can be tolerated in air, carbon monoxide is at least one hundred times more dangerous than carbon dioxide.

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[7] Haldane, J. S., and Smith, Lorain, Physiological effects of air vitiated by respiration, J. Path. Bact. **1**, p. 174; 1892.

[8] R. R. Sayers, Physiological effects due to the use of rescue apparatus, Coal Trade Bulletin, **45**, p. 28, 1921.

[9] The amount of air flowing through the lungs in a given time.

IV. EFFECT OF DIMINISHED OXYGEN SUPPLY

Normal, pure, dry air, when analyzed by volume, consists of 20.93 per cent oxygen, 79.04 per cent nitrogen, and 0.03 per cent carbon dioxide. Included in the nitrogen content is about 1 per cent of the four inactive gases, argon, krypton, neon, and xenon, argon largely predominating. Every cubic foot of natural gas (assuming the gas to consist of 88.7 per cent methane and 10.7 per cent ethane as used in these tests) requires 2.15 ft.^{3} of oxygen for complete combustion or 10.3 ft.^{3} of air. An ordinary standard domestic natural-gas burner should consume gas at a rate not greater than about 8 ft.^{3} per hour when at the proper distance from the utensil (1 in.). At a rate of 8 ft.^{3} of gas per hour, 82.4 ft.^{3} of air per hour will be required for complete combustion.

It is evident that in a closed room the oxygen percentage drops according to the rate of consumption of gas. In tests made with a burner consuming 8 ft.^{3} of natural gas per hour in an air-tight room of approximately 1000 ft.^{3} capacity it required 1.5 hours to reduce the oxygen content to 18 per cent. As a general average, the oxygen percentage probably never falls below 19 per cent. It is believed that ordinarily enough natural ventilation occurs to maintain an oxygen value of at least 19 per cent. Natural gas will not burn if the oxygen is reduced as low as 15.5 per cent. An individual when at rest, however, may tolerate oxygen percentages below 13 per cent without serious effects other than a sense of fatigue.

V. TESTS OF PRODUCTS OF COMBUSTION FOR CARBON MONOXIDE

It was shown in the efficiency tests of natural-gas burners of standard size that a consumption of 6 to 8 ft.^{3} per hour contained the maximum quantity of heat units that a standard burner would require if the burner were about 1 in. from the utensil. (See Bureau of Standards paper "How natural-gas burners can be improved," by I. V. Brumbaugh and G. B. Shawn.) Tests for carbon monoxide were made at these rates of consumption and different positions of utensil from burner, since the question of the maximum efficiency that can be safely secured with the various burners depended on how close to the utensil the burner could be placed without producing carbon monoxide in poisonous quantities.

There are many designs of natural-gas burners placed at different distances from the utensil, and the flame characteristics

of each are generally quite different. Even if the different designs of burners were placed at the same distance from the utensil, owing to the various air-shutter adjustments there would be still no uniformity of flame characteristic for the same rate of consumption. It was essential, therefore, to operate burners with definite ratios of volume of primary air injected into the burner to volume of gas consumed and at different rates of consumption and at the different positions of burner from utensil, in order to secure comparative data by which to determine the proper distance.

The method of operation and a description of the apparatus which was used to produce the different ratios of air to gas is described in Bureau of Standards Technologic Papers, No. 193, Design of atmospheric gas burners, by Walter M. Berry, I. V. Brumbaugh, G. F. Moulton, and G. B. Shawn; also in How natural-gas burners can be improved, by I. V. Brumbaugh and G. B. Shawn.

1. SAMPLING APPARATUS, METHOD OF SAMPLING, AND METHOD OF ANALYSIS

The apparatus for sampling the products of combustion was essentially as shown in Fig. 1. First, a definite number of cubic feet of gas per hour was supplied to the burner, and a definite number of cubic feet of primary air per hour was introduced into the burner through the air-shutter opening. Then an aluminum utensil *g* filled with 5 pounds of tap water was adjusted at a definite height over the burner. The hood *f* was then placed over the utensil and burner, and the products of combustion and the excess air were thus passed through the top of *f*. It was soon observed that the natural draft mixed too much excess air with the products of combustion. By closing a large portion of the opening at the top of the hood the excess air was decreased without interfering with the natural operation of the burner. About 2 minutes after the utensil was placed over the burner a sample of the products of combustion was taken, as follows: A gas sample tube *b* previously filled with water that was saturated with combustion product gases from the burners was connected to tube *d*. The tube *e* and connections were then cleared of dead gas by opening clamp *j* and working the bulb aspirator *a*. The water in sample tube *b* when pinch clamps *c* and *i* were opened was allowed to flow out, drawing in a sample of the products of combustion from the burner. When all but a few drops of water had left the

tube, the pinch clamps were closed and the sample was removed for analysis. At the beginning of the work repeat samples were taken 4 minutes after the utensil was placed above the burner. These samples in each case checked the 2-minute samples, and thereafter only one sample of gas was taken for each burner adjustment. The temperature of the water in the utensil was approximately 100° F (37.8° C) at the time of sampling.

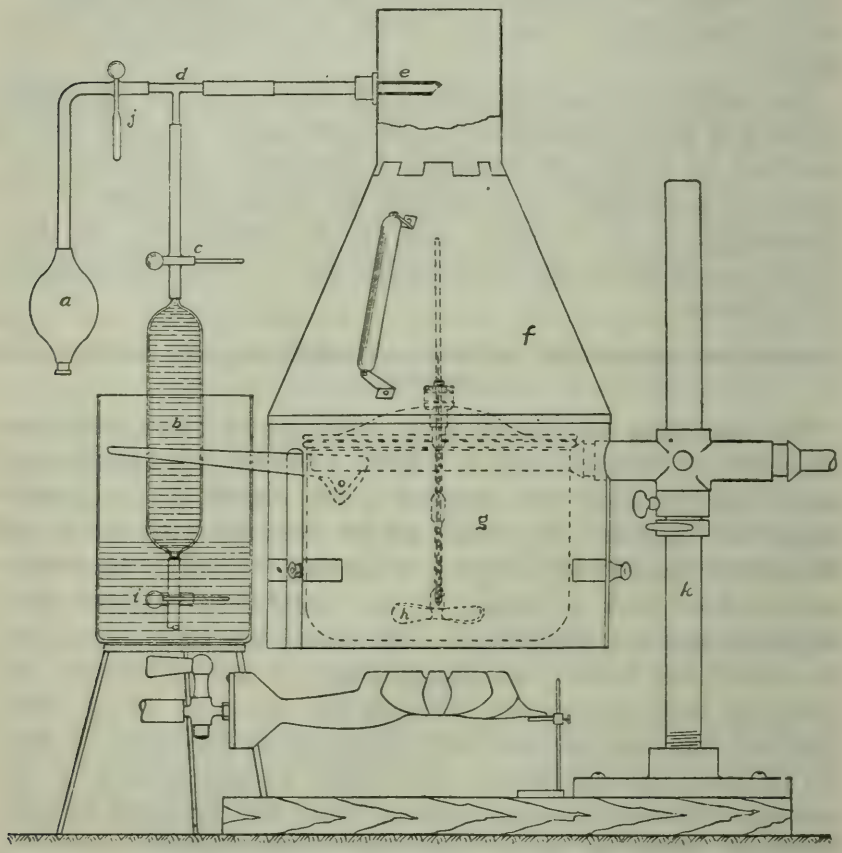

FIG. 1.—*Apparatus used for obtaining sample of products of combustion from burners.*

The samples were analyzed on the Haldane gas analysis apparatus of the usual type used by the U. S. Bureau of Mines for analyses of mine air samples. This apparatus has a limit of accuracy for carbon dioxide, oxygen, carbon monoxide, hydrogen, and methane of 0.02 per cent. For method of use and other details see U. S. Bureau of Mines Bulletin 42, The sampling and examination of mine gases and natural gas, by G. A. Burrell and F. M. Seibert.

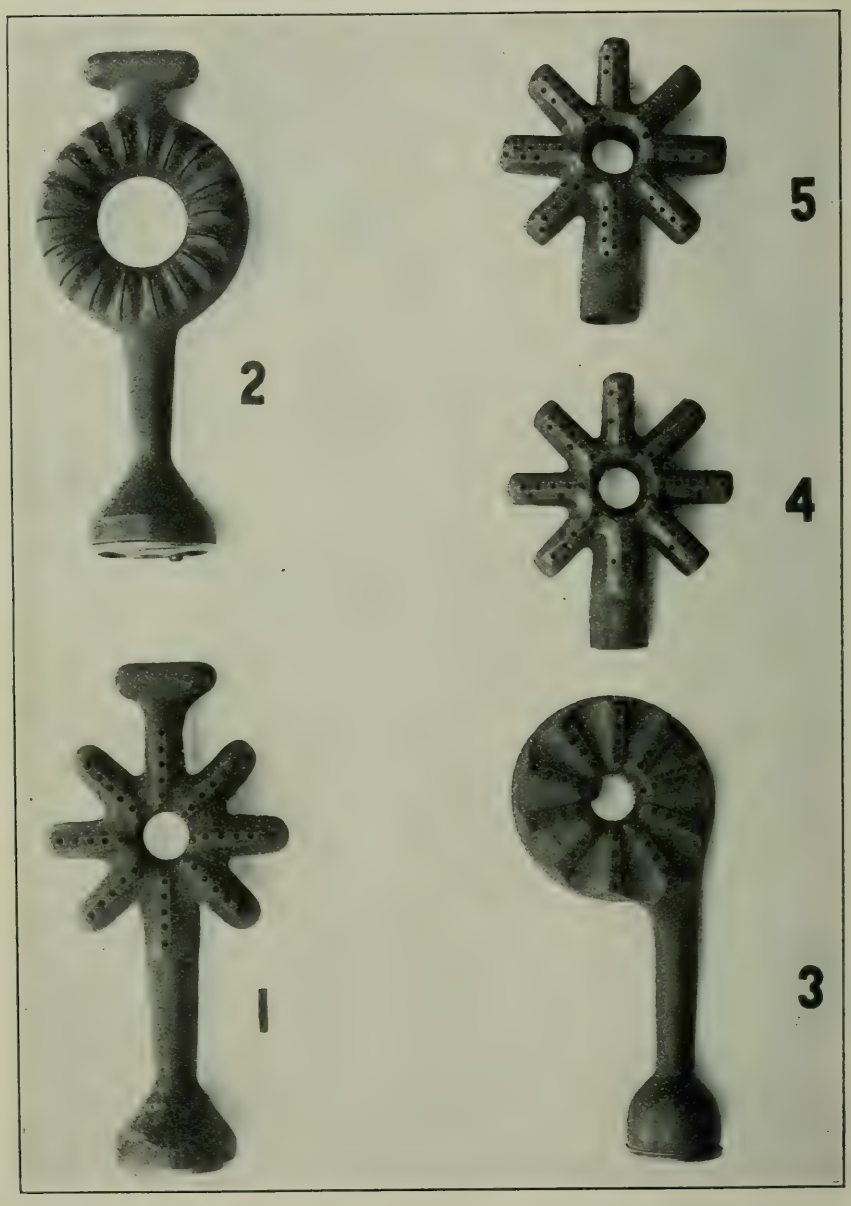

FIG. 2.—*Burners used in testing products of combustion for carbon monoxide*

2. BURNERS TESTED

The five different burners which were used to make the tests herein reported are shown in Fig. 2. Of the present domestic burners in operation with natural gas the type shown by No. 1, and known as the "star" burner, is most commonly used. No. 2 is called the "slot" or "sawed" burner, and No. 3 is of the "disc" type. Burners Nos. 4 and 5 are star burners with specially spaced ports. These two burners were fitted to improved injecting tubes when tested. The photograph shows them without the injecting tubes. Burners Nos. 1 and 3 were tested when the ports were of No. 40 drill size and also when of No. 30 drill size.

3. TABULATION OF RESULTS

The results of the tests of the products of combustion are tabulated in Table 1. The data are arranged to show separately the tests of each burner, because different types and different designs of any one type are rarely found in the same installation. The tests of the different positions of utensil from burner are grouped according to constant rates of consumption. The different rates of consumption are further grouped according to the ratio of volume of air injected into the burner to the volume of gas consumed.

TABLE 1.—Results and Conditions of Carbon Monoxide Tests

Type of burner	Gas rate	Air-gas ratio	Distance of utensil from burner	Cone height	Products of combustion air-free basis (per cent)				Formation of CO
					CO	CO_2	CH_4	N_2	
	Cu. ft.		In.	In.					Ft.³/hr.
Star burner (No. 1), 48 ports; No. 40 drill; port area, 0.36 sq. in.	6	1½:1	½	.....	0.35	11.53	0.09	88.03	[a]0.19
	6	1½:1	¾	.....	.35	11.48	.09	88.08	[a] .19
	6	1½:1	1	.....	.24	11.45	.02	88.29	.14
	6	3:1	½	0.48	.20	11.80	.10	87.90	[a] .11
	6	3:1	¾	.48	.34	11.95	.08	87.63	[a] .18
	6	3:1	1	.48	.11	12.02	.03	87.84	.06
	6	5:1	½	.40	.20	11.96	.05	87.79	[a] .11
	6	5:1	¾	.40	.08	12.01	.00	87.91	.04
	6	5:1	1	.40	.00	12.14	.00	87.86	.00
	8	1½:1	¾	.....	.29	11.48	.16	88.07	[a] .21
	8	1½:1	1	.....	.24	11.83	.09	87.84	[a] .18
	8	1½:1	1¼	.....	.32	11.88	.00	87.80	[a] .23
	8	3:1	½	.62	.23	11.48	.08	88.21	[a] .17
	8	3:1	¾	.62	.26	11.75	.06	87.73	[a] .19
	8	3:1	1	.62	.07	11.79	.04	88.10	.05
	8	5:1	½	.50	.10	11.46	.02	88.42	[a] .07
	8	5:1	¾	.50	.14	12.37	.00	87.39	[a] .10
	8	5:1	1	.50	.00	11.43	.00	88.57	.00
Star burner (No. 1); 48 ports; No. 30 drill; port area, 0.62 sq. in.	6	5:1	½	.37	.20	11.94	.03	87.83	[a] .11
	6	5:1	¾	.37	.36	11.78	.00	87.86	[a] .19
	6	5:1	1	.37	.14	11.92	.00	87.94	.08
	6	7:1	½	.27	.11	11.93	.00	87.96	[a] .06
	6	7:1	¾	.27	.06	12.44	.03	87.47	.03
	6	7:1	1	.27	.00	12.22	.00	87.78	.00
	8	5:1	½	.48	.16	11.77	.04	88.03	[a] .12
	8	5:1	¾	.48	.25	11.73	.04	87.98	[a] .18
	8	5:1	1	.48	.09	11.87	.02	88.02	.07
	8	7:1	½	.35	.27	11.82	.13	87.78	[a] .19
	8	7:1	¾	.35	.07	11.95	.05	87.93	[a] .05
	8	7:1	1	.35	.00	11.93	.00	88.07	.00

[a] Values which are averaged in Table 2.

TABLE 1.—Results and Conditions of Carbon Monoxide Tests—Continued..

Type of burner	Gas rate	Air-gas ratio	Distance of utensil from burner	Cone height	Products of combustion air-free basis (per cent)				Formation of CO
					CO	CO_2	CH_4	N_2	
	Cu. ft.		In.	In.					Ft.³/hr.
Disc burner (No. 3); 44 ports; No. 39 drill; port area, 0.34 sq. in.	6	3:1	¾	0.50	0.45	11.46	0.11	87.98	[a]0.25
	6	3:1	1	.50	.33	11.67	.00	88.00	[a].18
	6	3:1	1¼	.50	.05	11.81	.00	88.14	.03
	6	5:1	½	.38	.20	11.65	.00	88.15	[a].11
	6	5:1	¾	.38	.35	11.65	.11	87.89	[a].19
	6	5:1	1	.38	.06	11.92	.00	88.02	.03
	8	3:1	¾	.69	.28	11.84	.04	87.88	[a].20
	8	3:1	1	.69	.27	11.70	.04	88.03	[a].20
	8	3:1	1¼	.69	.15	11.87	.00	87.98	.11
	8	5:1	½	.50	.10	11.97	.04	87.92	[a].07
	8	5:1	¾	.50	.17	11.84	.06	87.99	[a].12
	8	5:1	1	.50	.10	11.95	.02	87.95	.07
Disc burner (No. 3); 44 ports; No. 30 drill; port area, 0.57 sq. in.	6	5:1	¾	.41	.32	11.97	.11	87.60	[a].17
	6	5:1	1	.41	.27	11.70	.00	88.03	[a].15
	6	5:1	1¼	.41	.03	11.63	.00	88.34	.02
	6	7:1	½	.34	.11	11.76	.05	88.08	[a].06
	6	7:1	¾	.34	.17	11.98	.03	87.82	[a].09
	6	7:1	1	.34	.00	12.39	.00	87.61	.00
	8	5:1	¾	.50	.21	12.08	.00	87.71	[a].15
	8	5:1	1	.50	.20	11.73	.07	88.00	[a].15
	8	5:1	1¼	.50	.10	11.82	.00	88.08	.07
	8	7:1	¾	.40	.18	11.99	.09	87.74	[a].13
	8	7:1	1	.40	.05	12.10	.00	87.85	[a].04
	8	7:1	1¼	.40	.00	12.10	.00	87.90	.00
Slot burner (No. 2); 18 slots; width 0.39 in.; port area, 0.64 sq. in.	6	5:1	½	.25	.32	12.12	.06	87.50	[a].17
	6	5:1	¾	.25	.09	11.96	.00	87.95	.05
	6	5:1	1	.25	.00	12.14	.00	87.86	.00
	6	7:1	½	.16	.06	11.97	.00	87.92	[a].03
	6	7:1	¾	.16	.00	12.00	.00	88.00	.00
	6	7:1	1	.16	.00	11.45	.00	88.55	.00
	8	5:1	½	.28	.16	11.82	.05	87.97	[a].12
	8	5:1	¾	.28	.08	11.87	.05	88.00	.06
	8	5:1	1	.28	.00	12.10	.00	87.90	.00
	8	7:1	½	.20	.16	12.00	.00	87.84	[a].12
	8	7:1	¾	.20	.00	12.09	.00	87.91	.00
	8	7:1	1	.20	.00	12.15	.00	87.85	.00
Star burner (No. 5); 67 ports; No. 36 drill; port area, 0.60 sq. in.	6	3:1	½	.40	.36	11.67	.05	87.92	.20
	6	3:1	¾	.40	.28	11.80	.00	87.92	.15
	6	3:1	1	.40	.00	11.90	.00	88.10	.00
	6	5:1	½	.31	.32	11.77	.08	87.83	.18
	6	5:1	¾	.31	.00	11.46	.00	88.54	.00
	6	5:1	1	.31	.00	11.97	.00	88.03	.00
	6	7:1	½	.25	.16	11.51	.10	88.23	.09
	6	7:1	¾	.25	.00	11.97	.06	87.97	.00
	6	7:1	1	.25	.00	11.84	.00	88.16	.00
	8	5:1	½	.37	.22	11.77	.02	87.99	.16
	8	5:1	¾	.37	.25	11.68	.00	88.07	.18
	8	5:1	1	.37	.07	11.90	.05	87.98	.05
Star burner (No. 6); 100 ports, No. 36 drill; port area, 0.90 sq. in.	8	3:1	½	.41	.17	11.57	.00	88.26	.13
	8	3:1	¾	.41	.08	11.53	.00	88.39	.06
	8	3:1	1	.41	.00	11.69	.00	88.31	.00
	8	5:1	½	.30	.13	11.70	.05	88.12	.10
	8	5:1	¾	.30	.15	11.70	.02	88.13	.11
	8	5:1	1	.30	.00	11.90	.00	88.10	.00
	8	7:1	½	.22	.12	11.57	.02	88.29	.09

[a] Values which are averaged in Table 2.

The values of the products of combustion on an air-free basis were computed as follows: Since normal air contains 20.93 per cent oxygen, if the oxygen percentage found in the sample of the

products of combustion is divided by 20.93, the resulting value gives the proportion of air present. This factor subtracted from 1.0 and divided into the different percentages of the analysis of the sample gives the air-free percentages shown in the table. For example, take the first analysis given in Table 1. The products of combustion, as sampled, contained:

	Per cent
CO	= 0.16
CO_2	= 5.20
O_2	= 11.48
CH_4	= .04
N_2	= 83.12
Total.....	100.00

Then, since the sample contained 11.48 per cent oxygen, $\frac{11.48}{20.93} = 0.549$, proportion of air in sample; and $1.0 - 0.549 = 0.451$, proportion of products of combustion in sample. Therefore, on the air-free basis,

	Per cent
CO	$= \frac{0.16}{0.451} =$ 0.35
CO_2	$= \frac{5.20}{0.451} =$ 11.53
CH_4	$= \frac{0.04}{0.451} =$ 0.09
N_2	= 88.03 by difference
Total....	100.00

The values of the rate of production of carbon monoxide in terms of cubic feet per hour shown in Table 1 were computed as follows: The average composition of the natural gas used in the tests contained:

	Per cent
Methane (CH_4)	= 88.7
Ethane (C_2H_6)	= 10.7
Nitrogen (N_2)	= .6
Total.....	100.0

The above values for methane and ethane were determined by calculation of the contraction and carbon dioxide produced when a given quantity of natural gas was burned by the slow combustion method. The method gives the percentage of the two predominating hydrocarbons present. In reality the natural gas used contained a small amount of propane and traces of butane. The only available method for obtaining more than two saturated paraffin hydrocarbons in a natural gas is by fractionation analysis at low temperatures and pressures, using liquid air in oxygen.

Since the above method of reporting as to the two predominating hydrocarbons is correct with regard to the carbon content in a cubic foot of gas, the more tedious and expensive method of analysis using liquid air was not used.

One cubic foot of methane when completely burned produces 1 ft.³ of carbon dioxide, as the following equation indicates:

$$CH_4 + 2O_2 = CO_2 + 2H_2O.$$

Also when partially oxidized to carbon monoxide, 1 ft.³ of carbon monoxide is produced per cubic foot of methane, thus

$$CH_4 + O_2 = CO + H_2O.$$

Therefore, whether methane is completely oxidized to carbon dioxide or partially oxidized to carbon monoxide, or remains as unconsumed methane, the total quantity of these gases from 1 ft.³ of methane will always equal 1 ft.³

When ethane is completely burned to carbon dioxide and water vapor, 1 ft.³ will produce 2 ft.³ of carbon dioxide according to the following equation:

$$C_2H_6 + 3\tfrac{1}{2}O_2 = 2CO_2 + 3H_2O.$$

Also, when partially oxidized to carbon monoxide each cubic foot of ethane produces 2 ft.³ of carbon monoxide; thus—

$$C_2H_6 + 2\tfrac{1}{2}O_2 = 2CO + 3H_2O.$$

Therefore, 1 ft.³ of ethane produces a total of 2 ft.³ of carbon dioxide and carbon monoxide irrespective of the relative percentages of each.

Going back to natural gas consisting of 88.7 per cent methane and 10.7 per cent ethane, in order to determine the total amount by volume of carbon monoxide produced per cubic foot of gas burned,

Multiply 0.887 by 1.0 = 0.887, and
Multiply 0.107 by 2.0 = 0.214,

which gives a total of 1.101 ft.³ of carbon monoxide and carbon dioxide per cubic foot of gas consumed.

Then let a = per cent of CO (air free basis)
b = per cent of CO_2 (air free basis)
c = per cent of CH_4 (air free basis)

and $\frac{a}{a+b+c} \times 1.101 \times$ gas rate per hour = the cubic feet of carbon monoxide produced per hour. This is the important column of the table with respect to health and ventilation.

4. POSSIBLE ERRORS IN ANALYSIS

From the manner of making analyses the following errors for the test for carbon monoxide could occur: (1) Incomplete absorption of the CO_2 in the sample before the test for combustion of CO is made; (2) incomplete absorption of CO_2 after combustion; (3) incomplete combustion of CO in the sample, assuming the CO_2 absorptions to be complete. It is possible, therefore, that there could be a greater error than 0.02 per cent in some analyses if any one of the above enumerations occurred. It is assumed that the possible error of 0.02 per cent referred to results from inability to compensate the volume and read the burette more accurately on account of the tedious method of manipulation of a Haldane gas analysis apparatus. If it is assumed that there can be a possible error of at least ± 0.02 per cent in the analysis of any constituent, then in the case where calculations are made on the air-free basis, if the sample contained 50 per cent air the air-free calculations can be in error by at least ± 0.04 per cent.

5. SIGNIFICANCE OF RESULTS

Observations made during the progress of the tests showed that at the close positions (generally ½ to ¾ in.) depending on design of burner, rate of consumption, and flame characteristic, the baffling of the flame hindered the supply of secondary air, forced the blue inner cone of the flame to spread, and, to use a familiar expression, caused a "floating flame" which extended up the side of the utensil. Under the "floating flame" condition rate of formation of carbon monoxide was a maximum for any given ratio of air to gas. The data show that there are no appreciable differences in the rates of formation of carbon monoxide for rates of consumption of 6 and 8 ft.^{3} per hour when the "floating flame" condition is produced.

In order to form some opinion as to the effect of design of burners and their operation, the amounts of carbon monoxide produced at the "floating flame" positions of burners Nos. 1, 2, and 3 are averaged in Table 2. The importance of operating natural gas burners with the air shutter adjusted for the higher ratio of air to gas is clearly shown by this table.

STAR BURNER NO. 1.—The average of 0.20 ft.^{3} of carbon monoxide per hour with star burner No. 1 was obtained when the ports were of No. 40 drill size, and the air-gas ratio was 1½ to 1. At such a ratio a yellow flame is produced that deposits carbon on

the utensil. By increasing the air-gas ratio to 5 to 1 a good blue flame was produced and the carbon monoxide was reduced to 0.09 ft.^{3} per hour. The burner could not be operated at a higher ratio because the velocity of the air-gas mixture issuing from the burner ports exceeded the velocity of combustion. The size of the ports of burner No. 1 was increased to No. 30 drill in order to operate it at a higher ratio, and Table No. 2 shows that the carbon monoxide average increased from 0.09 to 0.15 ft.^{3} per hour for an air-gas ratio of 5 to 1. At 7 to 1 ratio the carbon monoxide averaged 0.10 ft.^{3} per hour. Increasing the size of the ports increased the width of the flame of each port, thus bringing the flames closer together and causing poor aeration of the total flame.

TABLE 2.—Average from Carbon Monoxide Tests (from Table 1)

[Rate of consumption 6.0 and 8.0 ft.^{3} per hour; floating flame condition]

Air-gas ratio	Carbon monoxide produced with—							
	Star burner (No. 1)			Disc burner (No. 3)			Slot burner (No. 2)	
	Positions	48 ports		Positions	44 ports		Positions	
		No. 40 drill	No. 30 drill		No. 39 drill	No. 30 drill		
	In.	cu. ft.	cu. ft.		cu. ft.	cu. ft.		cu. ft.
1½:1	½, ¾, 1, and 1¼	0.20						
3:1	½ and ¾	.16		¾ and 1	0.21			
5:1	½ and ¾	.09	0.15	½, ¾ and 1	.12	0.16	½	0.14
7:1	½ and ¾	[a]	.10	½, ¾, and 1	[a]	.09	½	.07

[a] Could not be tested on account of limit of operation (flames blow from ports).

Disc burner No. 3.—Very similar results to those of the star burner were obtained with the disc burner, except that at respective ratios of air to gas a more appreciable amount of carbon monoxide was produced when the ports were of No. 39 drill size as compared with the star burner when the ports were of No. 40 drill size. This comparison is made not so much as to the size of ports but more especially for the total port area. The total port areas, as well as the size of ports, are approximately the same. There is no question but that the disk burner obstructs the flow of the supply of secondary air to the flame, which accounts for the higher amounts of carbon monoxide. The data show that the disc burner will produce slightly more carbon monoxide and at positions farther from the utensil than the star burner.

Slot burner No. 2.—The utensil must be ½ inch or closer to the slot burner to cause a floating flame with air-gas ratios of

5 to 1 and 7 to 1 at rates of 6 and 8 ft.^{3} per hour. This can be attributed to the short cone heights which are caused by the narrow slots. Since in general the closer a burner can be safely placed to the utensil, the higher the efficiency, the slot burner from this point of view should show better practical results than the star or disc type.

From the many tests, shown in Table 1, made under a variety of conditions, the maximum quantity of carbon monoxide was found to be 0.25 ft.^{3} per hour. Taking for comparison a room of 1000 ft.^{3} capacity, which can be considered as representative of the size of the average kitchen, and taking 0.04 per cent for the maximum limit of carbon monoxide permissible for healthful conditions for one hour's exposure, it would take over 1½ hours before the concentration reached 0.04 per cent if only one burner was operated and the room was unventilated. If as many as four burners were used under the same condition at one time, the carbon monoxide would have increased to 0.04 per cent in less than half an hour.

When one considers the natural ventilation which takes place through the windows and doors, it would seem that the danger from carbon monoxide poisoning from natural gas burners is quite remote. There may arise conditions where the housewife is working directly over a burner and may breathe the products of combustion containing dangerous percentages of carbon monoxide. These conditions would occur only at short intervals. The danger would be due not only to carbon monoxide, but to a slight extent to carbon dioxide and the deficiency of oxygen as well. Cases of this kind are probably very rare but possible. Owing to air currents set up in the room by the hot gases the carbon monoxide will always tend to be evenly diffused through the atmosphere.

6. EFFECT OF TEMPERATURE OF WATER IN UTENSIL ON CARBON MONOXIDE IN PRODUCTS OF COMBUSTION

In all the tests reported in Table 1 the water in the utensil was approximately 100° F (37.8° C) at time of sampling. Samples that were taken when the water was approximately 125° F (51.7° C) checked the 100° F samples. There was some question whether the rate of formation of carbon monoxide was as much when the water in the utensil was at boiling temperature. To compare the effect of temperature, the results of a few tests are given in Table 3. It is not clear why at the respective positions

more carbon monoxide was found with the star burner when the temperature of the water was 212° F as compared with 100° F, while the disk burner showed less carbon monoxide at 212° F as compared with 100° F. The data, therefore, are not definite and do not warrant a conclusion as to whether there is a difference in the rate of formation of carbon monoxide under the above conditions.

TABLE 3.—Effect of Temperature of Water on Carbon Monoxide in Products of Combustion (Air-free Basis)

[Star burner (No. 1), 8 prongs, 48 ports, No. 40 drill, 0.36 square inch port area]

Air-gas ratio	Position	Rate—6 ft.³ per hour, with—		Rate—8 ft.³ per hour, with—	
		Water approximately 100° F	Water boiling 212° F	Water approximately 100° F	Water boiling 212° F
	In.	Per cent	Per cent	Per cent	Per cent
3:1	½	0.20	0.28	0.23	0.29
	¾	.34	.40	.26	.33
5:1	½	.20	.39	.10	.13
	¾	.08	.10	.14	.23

[Disc burner (No. 3), 10 rows of ports—44 ports, No. 30 drill, 0.57 square inch port area]

Air-gas ratio	Rate—8 ft.³ per hour with—		
	Position	Water approximately 100° F	Water boiling 212° F
	In.	Per cent	Per cent
5:1	¾	0.21	0.16
	1	.20	.14
7:1	¾	.18	.11
	1	.05	.05

VI. IMPORTANCE OF PROPER VENTILATION

It is well known that for healthful purposes it is especially important to have ample ventilation where the products of combustion from burners of natural-gas appliances are liberated into the atmosphere of a room. Therefore it is of unusual interest to know to what extent the oxygen supply to a flame could be diminished before the deficiency of oxygen resulting from combustion would cause the flame to be completely smothered. It is perhaps of greater importance to know how much of the highly poisonous carbon monoxide can be produced under the above condition which would correspond to poor ventilation. To obtain such data a test was made when a burner was operated in a specially constructed air-tight room with no ventilation.

A standard star burner containing 48 ports of No. 40 drill size was used for the test. The burner was adjusted so as to burn with a yellow flame, which is characteristic of many of the worst installations of natural-gas burners. Approximately one and one-half volumes of air to one of gas were injected into the burner with the gas. The gas rate was regulated so that the burner consumed about 8 ft.^{3} of natural gas per hour. After these preliminary regulations had been made an aluminum utensil was filled with water and placed 1 inch above the burner. The outlets of the room were then closed and the time recorded. A sample of the atmosphere in the room was taken each half hour until the flame went out. Just before taking each sample, the fan in the room was run for about 3 minutes to thoroughly mix the products of combustion with the atmosphere inside the room.

Table 4 shows the results of the test from the time when the burner was lighted until the flame went out. The curves of Fig. 3 show graphically the increase of carbon dioxide and decrease of oxygen, the increase of nitrogen, the increase of methane and increase of carbon monoxide. The test shows very clearly the necessity of having good ventilation in rooms where burners are used for long periods of time. The room had a capacity of approximately 1000 ft.^{3}, which is believed to be near the capacity of the average kitchen. The burner using about 8 ft.^{3} of gas per hour at the end of 1.5 hours reduced the oxygen percentage from 20.9 to about 18 per cent and the carbon dioxide percentage rose to over 1.5 per cent. At the time the flame went out the oxygen content in the room had been reduced to less than 15.5 per cent and the carbon dioxide content was 3 per cent. The atmosphere also contained 0.16 per cent of carbon monoxide, which was an extremely poisonous concentration.

TABLE 4.—Analysis of Atmosphere in Unventilated Room of 1000 Cubic Feet Capacity

Test	Hours after beginning test	Gas consumed (cu. ft.)	Temperature of room[a]	Percentage composition of air in room					Remarks
				CO_2	O_2	CO	CH_4	N_2	
			°F						
1	0.0	0.0	78.5	0.03	20.93	0.00	0.00	79.04	Start of test
2	.5	.....	89.5	.58	19.92	.02	.02	79.46	
3	1.0	.....	93.0	1.07	19.02	.04	.02	79.85	
4	1.5	.....	96.0	1.60	18.05	.05	.05	80.25	
5	2.0	.....	97.0	2.08	17.24	.05	.05	80.58	
6	2.5	.....	97.0	2.51	16.38	.08	.07	80.96	
7	3.0	.....	98.5	2.89	15.51	.16	.11	81.33	
8	3.11	[b] 25.78	98.5	3.02.	15.43	.16	.11	81.28	End of test. Flame went out

[a] Barometer 29.24 in. Hg. [b] Corrected to 30.0 in. Hg and 60° F.

In general, natural ventilation due to opening doors and leakage around the window casings will tend to keep the percentages of oxygen and carbon dioxide near that of normal air as well as to dissipate the carbon monoxide in proportion. The amount of natural ventilation will vary over a very wide range with different

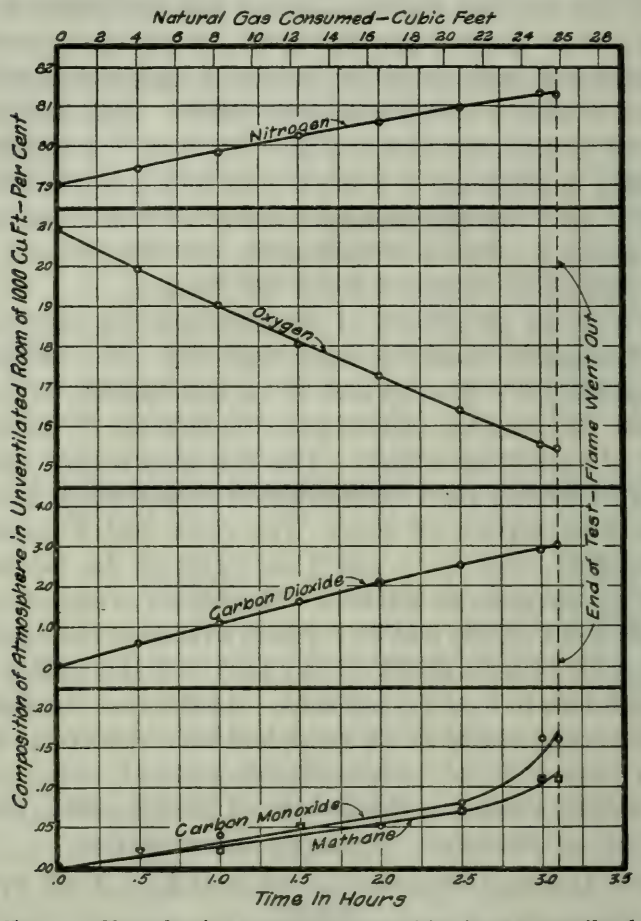

FIG. 3.—*Chart showing percentage composition in an unventilated room of 1000 ft.³ capacity as natural gas was burned in a top range burner at a rate of about 8 ft.³ per hour until the flame was smothered from deficiency of oxygen*

rooms and different seasons of the year, and it is therefore impossible to show accurate data as to what the values would be under practical conditions. On the other hand, the results of the test given in Table 4 show the maximum values to be expected from one burner where there is no natural ventilation and where the rate of consumption is about 8 ft.³ of natural gas per hour. If

the rate of consumption had been increased, or if more burners had been operated, the time that would have been required to cause the same smothering of the flame would have been proportionately decreased according to the rate of consumption.

It follows that if about 26 ft.^{3} of natural gas of the quality used in the tests of this report, under the conditions stated, are consumed in an unventilated room with a capacity of approximately 1000 ft.^{3} it will cause the flame to be extinguished from the diminution of oxygen. It is also evident that it is possible to have carbon monoxide present in an extremely dangerous quantity in poorly ventilated rooms where the yellow flame from natural-gas burners impinges against a utensil.

The fact that natural gas will not burn in an atmosphere where the oxygen content has been reduced to about 15.5 per cent explains why the flame from a burner is sometimes found extinguished when no one has caused it to be extinguished. This very seldom occurs except in winter months when proper ventilation is not observed. In the natural-gas regions deaths from smothering have occurred in extremely cold weather when people before retiring for the night have closed up the cracks around windows and doors so as to stop ventilation in order to retain the heat from a room heater and thereby have a warm room in which to sleep.

VII. CONCLUSIONS

Tests of the combustion products from burners using natural gas and burning in contact with utensils containing liquids at or below the boiling point of water show that carbon monoxide is liberated.

The quantities depend upon:

1. Distance of the utensil above the burner.
2. Height of blue inner cone of flame.
3. Type of burner.
4. Flame characteristic. (Ratio of volume of primary air injected into burner relative to volume of gas consumed.)
5. Rate of consumption of gas per hour.

It was observed that no carbon monoxide was found where the distance of the utensil from the burner was such that the blue inner cone of the flame did not touch the utensil.

For the same rate of consumption and same ratio of primary air to gas, one design of burner may permit the utensil to be placed as close as ¾ inch while another design may require a distance

of more than 1¼ inches in order that the amount of carbon monoxide be negligible.

For a given ratio of primary air to gas the highest percentages of carbon monoxide are produced when the utensil is placed so close to the burner as to cause a floating flame. When using the same burner with the utensil at a position that causes the flame to float, the carbon monoxide increases as the primary air rate is decreased. Therefore, a yellow flame will produce carbon monoxide at a rate greater than a blue flame.

Much of the carbon monoxide is surely produced by the smothering of the flame with the products of combustion which are hindered in their escape at the close positions of utensil from burner by the unavoidable baffling of the supply of secondary air. It is generally reported that carbon monoxide is produced by the chilling of the flame with a relatively cold surface.

Under the worst conditions found, the amount of carbon monoxide liberated per hour by the five gas burners tested was not enough to be dangerous to health unless one worked directly over the burner, or several burners were in use at the same time for several hours, or the room was unventilated.

Ventilation is essential where gas is consumed. A natural-gas flame will be smothered by the deficiency of oxygen when the oxygen content of the atmosphere has been diminished to about 15.5 per cent.

WASHINGTON, November 1, 1921.

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POWER LOSSES IN AUTOMOBILE TIRES

BY

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Bureau of Standards

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POWER LOSSES IN AUTOMOBILE TIRES

By W. L. Holt and P. L. Wormeley

ABSTRACT

This paper relates to the power loss or energy dissipated as heat in automobile tires when operated under different conditions of axle load, inflation pressure, speed, and tractive effort.

The special equipment used consists of two electrical absorption dynamometers, one operated as a motor and carrying on its shaft a wheel and the tire to be tested and the other operated as a generator and carrying on its shaft a smooth, flat-faced metal drum. The motor is mounted on a movable carriage, the arrangement being such that the tire can be forced against the drum with a pressure corresponding to the desired axle load. In this way the tire and drum constitute a friction drive by means of which the motor drives the generator. The field pole frame of each dynamometer is supported in ball bearings concentric with the armature shaft, and when in operation the magnetic drag or torque is measured on a scale. The power loss in the tire is the difference between the energy delivered by the motor to the tire and the energy delivered by the tire to the drum. This is determined from the speed of the motor and of the generator in conjunction with the torque on the respective field pole frames.

1. OBJECT AND SCOPE OF THE INVESTIGATION

The Bureau of Standards has undertaken a general investigation of automobile tires and inner tubes, and in connection with this work a rather comprehensive program has been laid out for dynamometer tests, to study among other things the power losses or energy dissipated as heat in tires operated under different conditions of axle load, inflation pressure, speed, temperature, and tractive effort. Preliminary tests have been made to determine the influence of these factors, which, aside from matters of design, are the principal items affecting the power loss in a tire. A continuation of the work will involve problems of design and construction, the influence of "over size" tires and of "cord tires" on power losses, mileage, and general efficiency of operation. An investigation will be made of inflation pressures as affecting the efficiency and economy of tire operation. Tests will be made to determine the effects of tire fillers, shields, puncture-proof tubes, etc., and the properties of cushion tires will be studied.

Tire dynamometers, although designed primarily for investigational work, are adapted for routine testing to determine the relative durability of tires and inner tubes. The surface of the

drum (see Fig. 8) being smooth, there is little wear of the tread rubber, and the tire fails ultimately as a result of ply separation, which is the usual cause of failure in service, or a blow-out takes place at some weak spot which has developed during the test. It is necessary to determine the quality of the tread stock by physical tests and chemical analyses.

It has been suggested that a number of detailed requirements in the existing Government specifications be eliminated and that a laboratory service test be substituted therefor. In working out a plan such as this the results of dynamometer tests will be of great value in designing a standard tire-testing machine and in interpreting the results intelligently. In order to interpret the results of a dynamometer endurance test in terms of the probable mileage that a tire would give on the road, it will be necessary to make a large number of comparative tests under careful observation. The Bureau plans to conduct a series of such tests.

2. EQUIPMENT

The equipment (see Fig. 8) consists of two Sprague electrical absorption dynamometers having a capacity of 20 horsepower at 600 revolutions per minute and 10 horsepower at 150 revolutions per minute. One dynamometer is operated as a motor carrying on its shaft a wheel and the tire to be tested. The other dynamometer is operated as a generator carrying on its shaft a smooth straight face iron drum 40 inches in diameter. The motor is mounted on a movable carriage, the arrangement being such that by the application of weights to a bell-crank lever the tire is forced against the drum with a pressure corresponding to the desired axle load. In this way the tire and drum constitute a friction drive by means of which the motor drives the generator. The field pole frame of each dynamometer is supported in ball bearings concentric with the armature shaft, and when in operation the magnetic drag or torque is measured on a Fairbanks beam scale. Each dynamometer is provided with a centrifugal tachometer which indicates the approximate speed in revolutions per minute and with a mechanical revolution counter operated by a magnetic clutch. The revolution counters are so designed that they may be read to the nearest one-tenth revolution of the tire or drum. The control panel is completely equipped for regulating the motor speed and generator load. Resistance grids are provided for absorbing the power generated. A switch is provided

for operating simultaneously a stop watch and the revolution counters.

The inflation pressure is measured or changed while the tire is running, as follows: The tire valve, with the inside parts removed, is connected by a small tube to an attachment on the hub which communicates through a slip joint with a stationary chamber. This chamber is provided with a needle valve for closing the air passage leading from the tire, a standard tire valve for inflating or deflating the tire, and a connection for a tube leading to a pressure gage.

3. METHOD OF DETERMINING POWER LOSS

The distance from the center of the shaft to the knife-edge on each element is 15.756 inches, so that the power output of the motor and the power imput of the generator are computed by the formulas

$$HP_1 = \frac{T_1 N_1}{4000} \quad \ldots\ldots (1),$$

and, $$HP_2 = \frac{T_2 N_2}{4000} \quad \ldots\ldots (2).$$

Where T_1 = scale reading of motor element in pounds (corrected for windage),

T_2 = scale reading of generator element in pounds (corrected for windage),

N_1 = revolutions per minute of tire,

N_2 = revolutions per minute of drum.

The correction for windage of the wheel and tire is determined by noting the scale reading at various speeds with the tire out of contact with the drum. This is a minus correction. The correction for windage of the drum is determined by running the generator element as a motor and noting the scale reading at various speeds. This is a plus correction. The value of the windage corrections is very small. For example, the average corrections for a 33×4 tire run at 25 miles per hour, including both motor and generator, are equivalent to about 0.03 horsepower.

The power loss in a tire is given by the equation:

$$HP_1 - HP_2 = \frac{T_1 N_1 - T_2 N_2}{4000} \text{ (horsepower)} \quad \ldots\ldots (3).$$

This loss is due partly to deformation of the tire and partly to slip. The part due to deformation represents heat developed in the tire, and the part due to slip represents heat developed at

the surface of contact between tire and drum. The loss due to deformation of the tire may be viewed as consisting of two parts: (1) That due to a radial force (axle load) and (2) that due to a tangential force (tractive effort). The loss resulting from axle load is indicated by rolling resistance, which is defined as the resistance to turning (measured at the drum surface) which the tire would offer if there were no tractive effort. An approximate value for this loss is obtained by substituting in equation (3) values of T_1, T_2, N_1, and N_2, observed when running the tire with no load on the generator.

When there is a tractive effort, the tangential component of the drum's reaction against the tire acts as a drag on the tread rubber. This tangential force has the double effect of compressing the tread rubber circumferentially just before it comes in contact with the drum and of producing a shearing action between the tread and carcass, with a corresponding circumferential or angular deformation of the carcass. This circumferential deformation of the tire produces creep in a manner similar to the creep of a belt on a pulley, since the material of the tire approaches the point of contact with the drum under compresssion and leaves it under tension. Portions of this surface of the tire are slipping on the drum, but it is probable that this slipping is confined to the ends of the surface of contact. The difference between the circumferential speed of the tire and drum is therefore more in the nature of a "creep" than what is ordinarily considered a "slip." If the tractive effort were increased sufficiently to produce "spinning" of the tire, the effect could more properly be called a "slip." The cushion forms an elastic bond between the tread and carcass and has its effect in producing creep, although this effect is not susceptible of measurement separately.

It is impossible to measure separately the losses due to creep and slip, but the sum of these losses may be approximated as follows: The pitch circle of the tire is defined as that circle which has the same linear velocity as that of the drum's surface when there is no tractive effort. We have therefore the relation—

$$\frac{r_1}{r_2}=\frac{n_3}{n_1} \qquad (4),$$

where r_1 = pitch radius of tire in feet,
r_2 = radius of drum in feet,
n_1 = revolutions per minute of the tire,
n_3 = revolutions per minute of the drum.

This equation is true, assuming that the slight tractive effort (about 2 pounds) which is introduced by friction in the generator is not appreciable.

If the observed speed of the drum is n_2 revolutions per minute when the tire is run under traction at a speed of n_1 revolutions per minute, we have

$$\text{Creep and slip} = 2\pi \frac{(r_1 n_1 - r_2 n_2)}{2\pi r_2}$$

$$= n_1 \frac{r_1}{r_2} - n_2 \text{ (revolutions per minute of the drum)} . \quad (5).$$

The corresponding power loss due to creep and slip is

$$HP_3 = \frac{T_2}{4000}\left(n_1 \frac{r_1}{r_2} - n_2\right) \text{ horsepower} \ldots\ldots\ldots\ldots (6).$$

4. RESULTS

Fig. 1 shows the effect of tractive effort on the power loss at different inflation pressures. (This tractive effort is taken as the

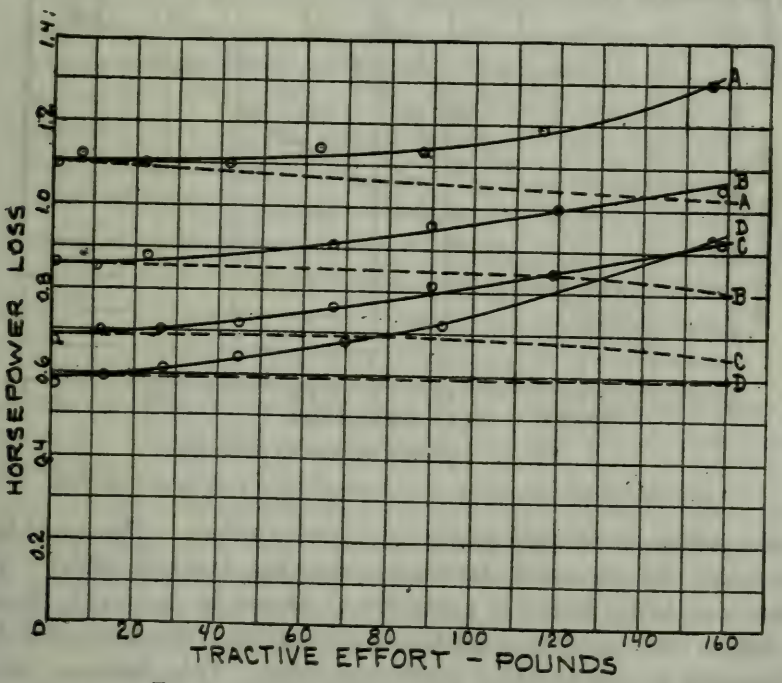

FIG. 1.—*Influence of tractive effort on power loss*

33×4 cord tire; speed, 25 mi. per hr.; axle load, 885 lbs.; air pressure in lbs./in.², A, 30; B, 45; C, 65; D, 90

resistance at the drum surface as calculated from the generator scale reading.) The total power loss as computed from equation (3) is shown in full lines. The dotted lines show the loss cor-

rected for creep and slip as computed from equation (6). The sum of the creep and slip and the resulting power loss increase with the tractive effort, the rate of increase becoming greater as the tractive effort becomes greater.

It appears that for a well-inflated tire the loss corrected for creep and slip, as shown in curve D, is constant, that is, independent of the tractive effort and is equal to the loss due to rolling

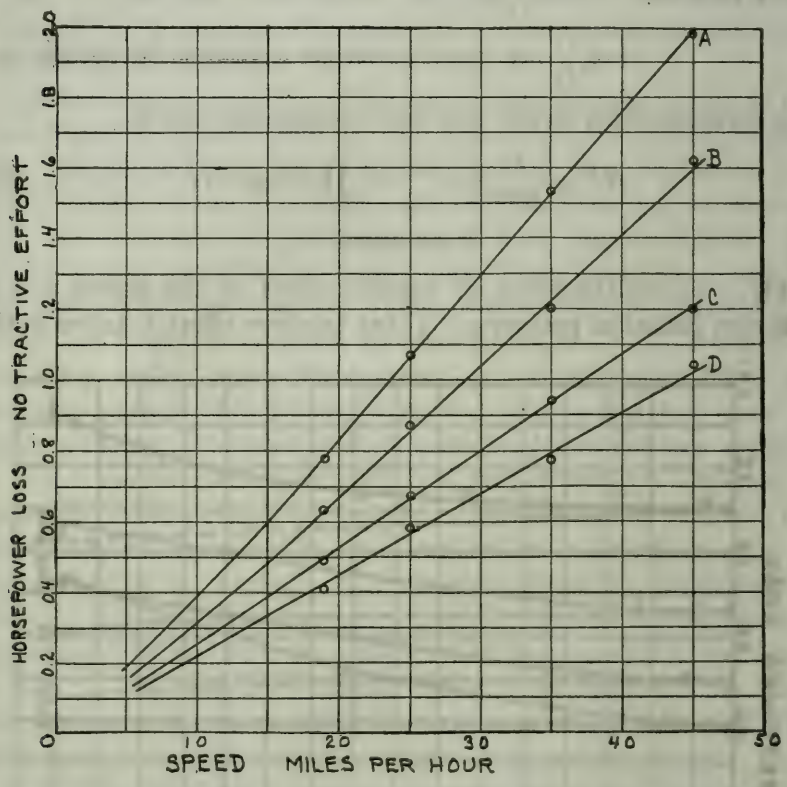

FIG. 2.—*Influence of speed on power loss*

33×4 cord tire; axle load, 885 lbs.; air pressure in lbs./in.², A, 30; B, 45; C, 65; D, 90

resistance as measured under no tractive effort. The total loss, as would be expected, increases with the tractive effort. The results at lower inflation pressures as shown in curves A, B, and C follow the same general trend except that the corrected loss decreases as the tractive effort increases. This decrease under increased tractive effort results from a circumferential shearing deformation of the carcass (which is negligible under high inflation pressure), causing an appreciable increase of creep. Hence, the correction for creep and slip includes a part of the carcass loss.

Fig. 2 shows the effect of speed on power loss at four different air pressures when a tire is run under constant axle load. The loss is nearly proportional to the speed, the rate of increase being greater as the air pressure decreases.

Fig. 3 shows the effect of axle load on power loss under four different air pressures when a tire is run at a constant speed. In this case also the loss is about proportional to the load, the rate of increase being greater as the air pressure decreases.

Fig. 4 shows the effect of inflation pressure on power loss under three different axle loads when a tire is run at constant speed.

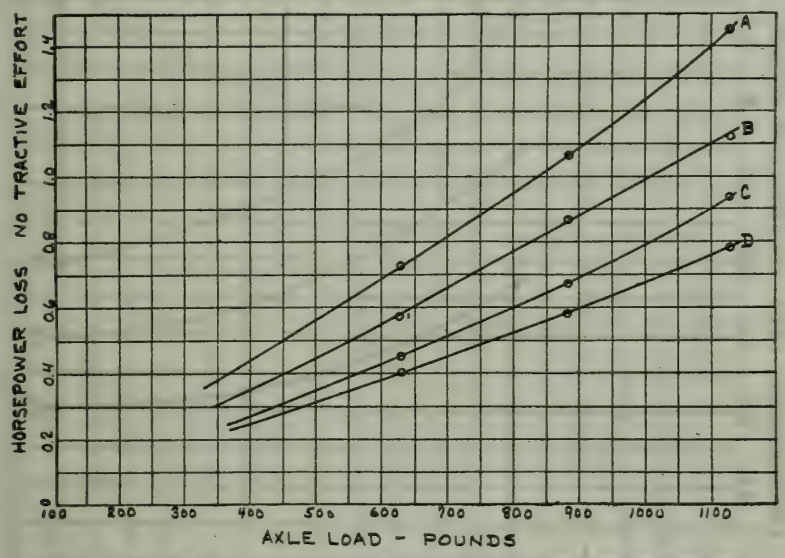

FIG. 3.—*Influence of axle load on power loss*

33×4 cord tire; speed, 25 mi. per hr.; air pressure in lbs./in.², A, 30; B, 45; C, 65; D, 90

In these cases there is a rapid increase in power loss under low air pressures. Under high air pressures the loss approaches a constant value.

Fig. 5 shows the influence of temperature on power loss. Tires were started at room temperature in each case, in which condition the losses are comparatively high. The pressure was kept constant, and at the end of about 30 minutes tires had become warm and losses had decreased to a normal figure and remained constant.

Fig. 6 shows one of the results of the power loss, an increase in temperature and pressure in the tire. The curves showing temperature rise are based on the assumption that the volume of air in the tire remains constant, and that the capacity of the connecting tubes and the gauge are negligible. The initial temperature

and pressure having been measured, the temperature at any time during the run is computed from the equation:

$$t = T\frac{P_2}{P_1} - 460 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7),$$

where t = temperature in tire in °F,
T = absolute temperature in tire at beginning of run,
P_1 = absolute pressure in tire at beginning of run,
P_2 = absolute pressure in tire corresponding to the temperature t.

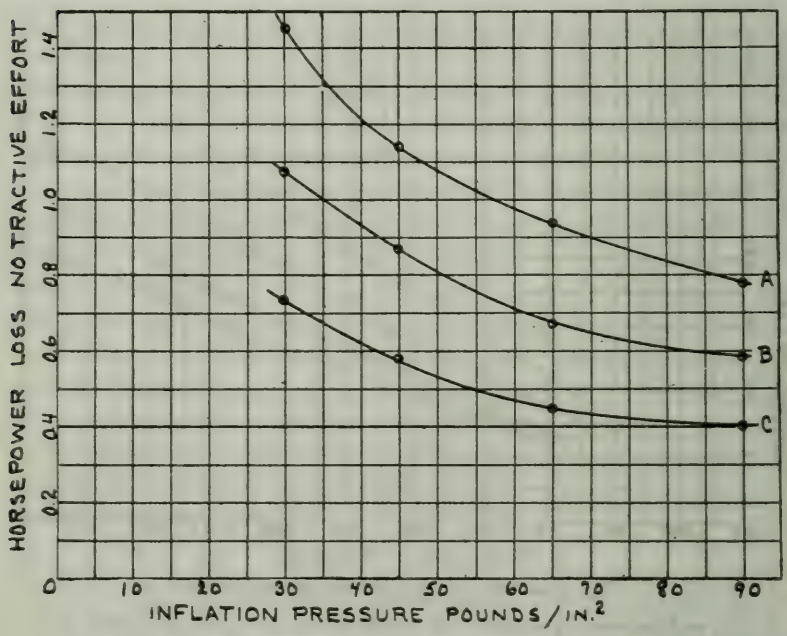

FIG. 4.—*Influence of inflation pressure on power loss*

33×4 cord tire; speed, 25 mi. per hr.; axle load in lbs., A, 1130; B, 885; C, 625

Fig. 7 is similar to Fig. 4, except that it shows a comparison of eight tires of different makes. The greater power loss in fabric tires shows up very plainly.

The question may arise as to the practical value of determining power losses in tires. These losses represent the energy absorbed by the tire and dissipated as heat while transmitting power from the axle to the road. They are due principally to internal strains in the tire, largely in the carcass. A large power loss results in (1) a correspondingly high fuel consumption, (2) quicker deterioration of the rubber and fabric on account of increased strains and increased temperature.

As examples of the association of power loss with the life of tires, the loss in a 4 inch fabric tire is in the neighborhood of 40 per cent higher than in a cord tire, even where both are the same size. Based on the ordinary mileage guarantees, the life of a fabric tire is about 40 per cent less than that of a cord tire. A 35×5 cord tire was found in which the power loss was abnormally high. A subsequent examination of the tire showed that al-

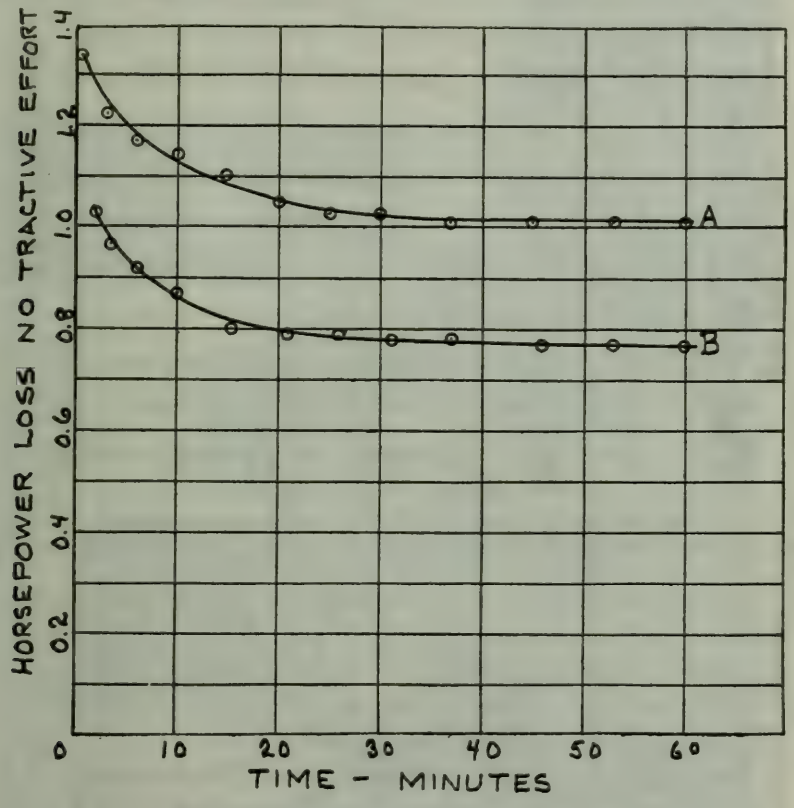

FIG. 5.—*Influence of temperature on power loss*

Speed, 25 mi. per hr.; axle load, 885 lbs.; air pressure, 60 lbs./in.²; tire A, 33×4 fabric; tire B, 33×4 cord

though it was constructed in the usual way and with proper materials, the coats of rubber between the plies were very thin, a feature which would have resulted in a short life. Hence, the fact that the tire was not up to the proper standard was determined in the laboratory within a very short time without injury to the tire.

One point which should be recognized is that the power loss alone does not show the value of a tire from the standpoint of

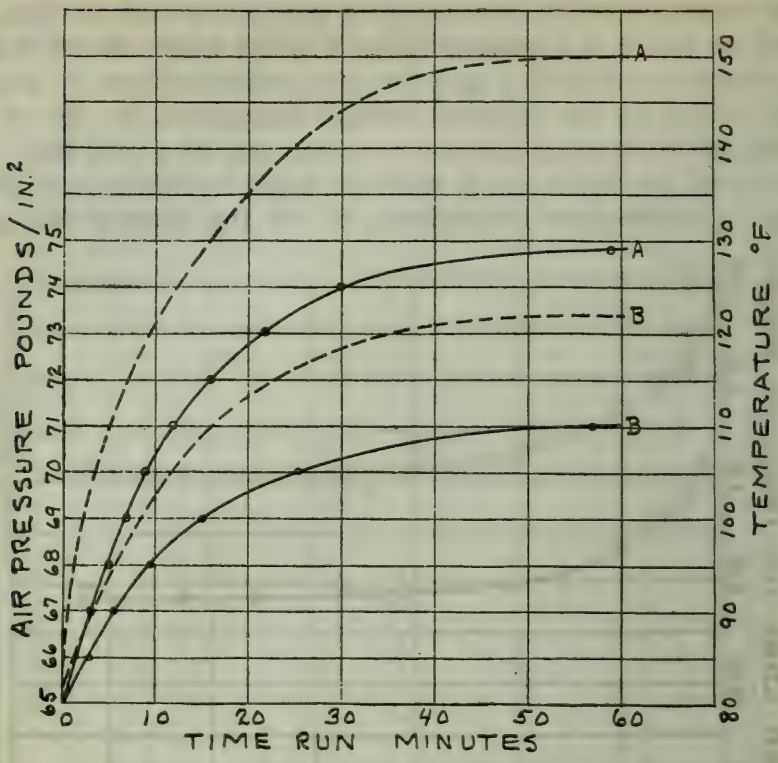

FIG. 6.—*Rate of increase of inflation pressure and temperature*

Speed, 25 mi. per hr.; axle load, 885 lbs.; air pressure, 65 lbs./in.²; tire A 33×4 fabric; tire B 33×4 cord; full lines, pressure rise; broken lines, temperature rise

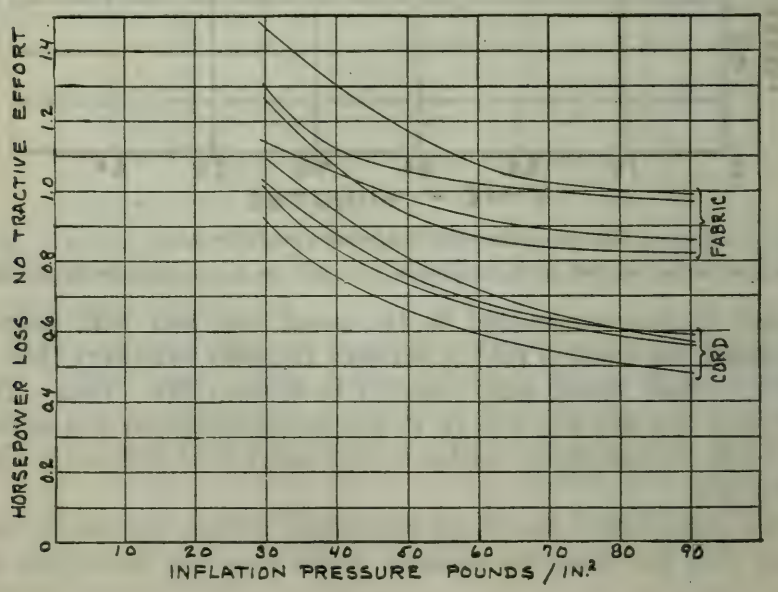

FIG. 7.—*Comparison of tires*

4 33×4 cord tires, 4 33×4 fabric tires. Influence of inflation pressure on power loss; speed, 25 mi. per hr.; axle load, 885 lbs.

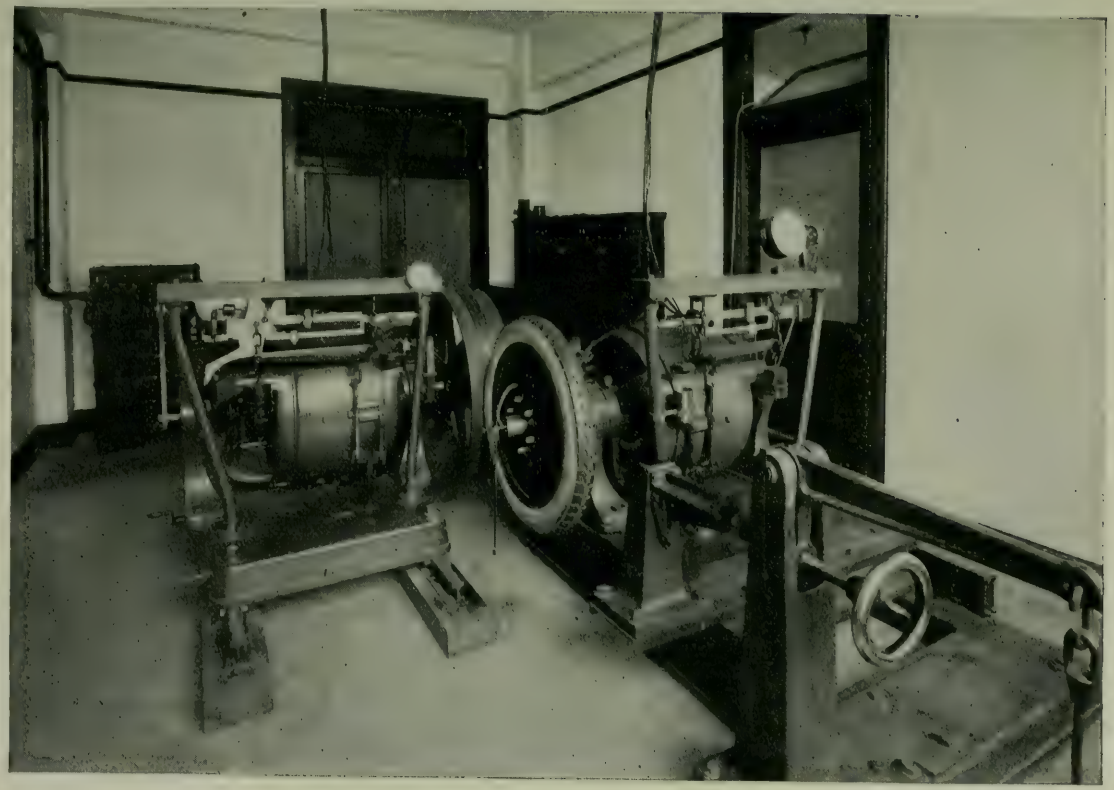

FIG. 8.—*Equipment used in measuring the power losses*

service, but, other things being equal, it should aid in determining the quality. For instance, the tire could be built with a reduced number of plies, which, with proper proportioning of rubber, might give a lower power loss. However, in service the tire would probably not be sufficiently rugged to withstand the ordinary blows to which a tire is subjected. A tire could be built of a very hard material, such as steel, which would result in a very small loss. The cushioning properties, however, would be entirely lacking. But, if we take two tires of the same general design, the one having the materials and construction so coordinated as to give a lowest power loss should have a longer life.

Aside from the question of design of tires, the power losses under different loads and air pressures indicate the proper conditions under which a tire should be run. In case of changes in these conditions the effect on the life of the tire is at least indicated by the corresponding change in power loss.

5. CONCLUSIONS

These preliminary results on power losses in tires show that, in general, the loss increases directly with an increase in speed or axle load and that it increases quite rapidly with decrease in air pressure below the standard. Tractive effort has a comparatively small effect on the power loss. There is a wide variation in the power loss in different tires run under the same conditions. Some makes of tires show a larger power loss than others, and fabric tires as a class show a considerable greater loss than cord tires. A continuation of this work in conjunction with a study of tire constructions and the action of tires under running conditions should give information which will help in developing better tire specifications and be an aid to the tire manufacturer.

WASHINGTON, December 30, 1921.

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DURABILITY OF CEMENT DRAIN TILE AND CONCRETE IN ALKALI SOILS: THIRD PROGRESS REPORT (1919–20)

BY

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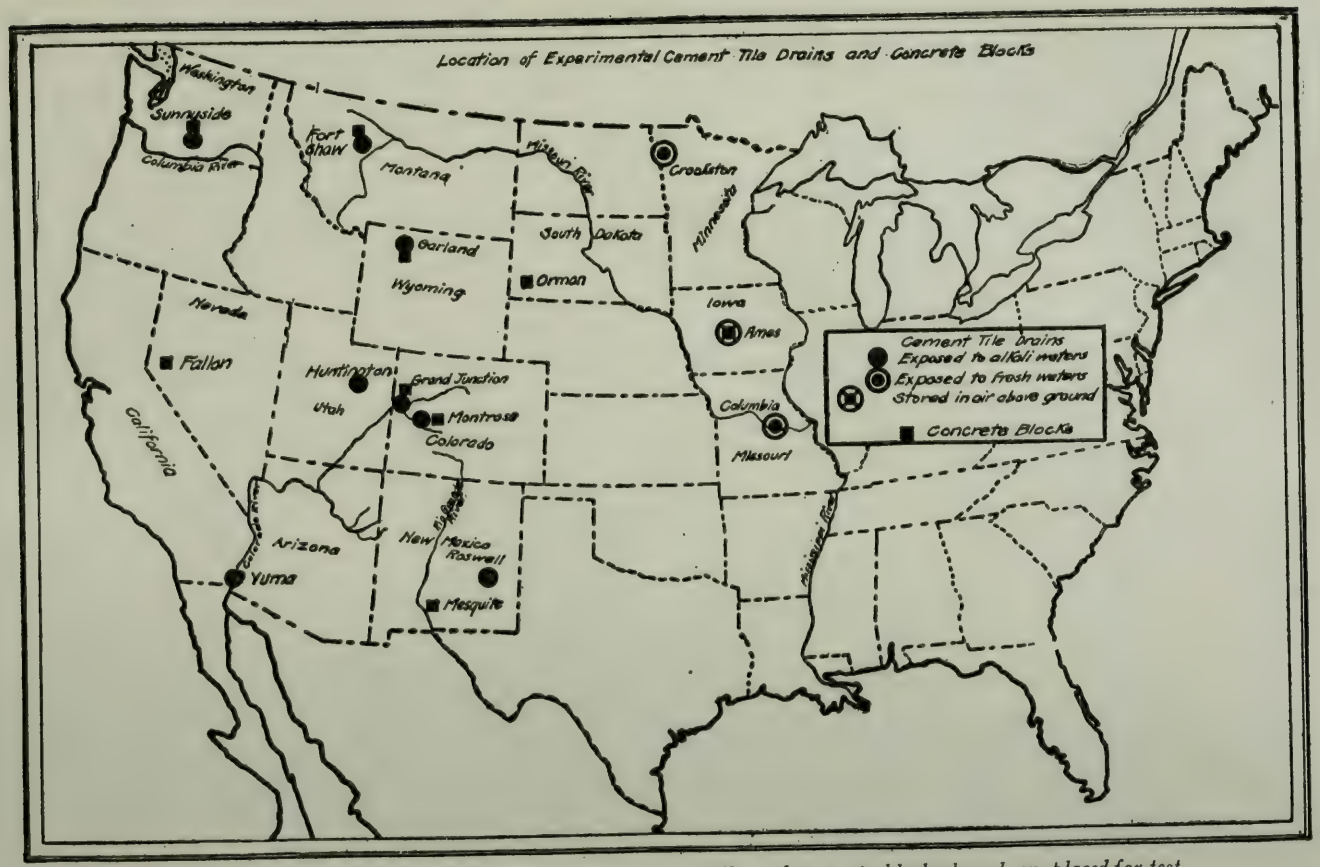

FIG. 1.—*Location of projects on which cement drain tile and concrete blocks have been placed for test*

To face page 463

DURABILITY OF CEMENT DRAIN TILE AND CONCRETE IN ALKALI SOILS: THIRD PROGRESS REPORT (1919-20)

By G. M. Williams

In cooperation with R. J. Wig, S. H. McCrory, E. C. Bebb, L. R. Ferguson, C. J. MacKenzie, D. A Abrams, and G. E. Warren

ABSTRACT

This paper reports the results of inspection in 1919 and 1920 of experimental drain tile and concrete block installations at eight alkali-bearing projects in the West. The investigation has been carried on since 1913, and the conclusions to date are that the best quality of concrete will disintegrate when exposed to severe alkali attack, and that installations of concrete in soils containing more than 0.1 per cent of salts of the sulphate type should be preceded by an examination of surrounding conditions.

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I. INTRODUCTION

The field investigation of the durability of cement drain tile and concrete in alkali soils and waters was started in 1913. A report giving details of manufacture and installation of test specimens was issued in 1915 as B. S. Technologic Paper No. 44, Investigation of the Durability of Cement Drain Tile in Alkali Soils, containing also the results of the first year's tests. This report is now out of print.

In 1917 a second report was issued as B. S. Technologic Paper No. 95, Durability of Cement Drain Tile and Concrete in Alkali Soils, containing results of the third year's tests. This report included the results of the tests of drain tile in 1916, after three years' exposure, and the results of inspection, after one year's exposure, of a large series of concrete blocks which were installed in 1915.

The field work was interrupted from 1916 to 1919 by press of war work, and again resumed in the fall of 1919 by tests and inspections at all drain and block sites.

Reference should be made to the previous report, B. S. Technologic Paper No. 95, for detailed information as to the manufacture, installation, and results of inspections of test specimens. Only the latest test data and sufficient of the early history of the investigation to give the reader some idea of the scope of the investigation are included herein.

TABLE 1.—Schedule of Mixtures and Processes of Manufacture of Drain Tile

Installation	Series	Proportions cement-sand by volume	Consistency [a]	Manufacture	Curing	Notes
Original installation.	1	1 : 2½	Plastic	Handmade	Sprinkling	
	2	1 : 2½	Quaking	do	do	
	3	1 : 2	Plastic	do	Steam	
	4	1 : 2	do	do	do	Dipped in cement grout.
	5	1 : 2	do	do	do	Dipped in hot tar.
	6	1 : 2	do	do	do	10 per cent ferrous sulphate in mixing water.
	7	1 : 3	do	Packer-head machine.	do	
	8	1 : 4	do	do	do	
	9	1 : 1½	do	do	Sprinkling	
	10	1 : 1½	do	do	Steam	
	11	1 : 3	do	do	Sprinkling	
	12	1 : 4	do	do	do	
	13	1 : 2½	do	do	Steam	
	14	1 : 3	Fluid	Handmade	Sprinkling	
	15	1 : 3	do	do	do	Sand cement used.
	16	1 : 4	Plastic	Packer-head machine.	Steam	From factory stock pile.
1914 replacement.	17	1 : 1½	Quaking	On jigging machine.	Damp sand	
	18	1 : 2	do	do	do	¼ inch maximum size aggregate.
1915 replacement.	19	1 : 2½	Plastic	Tamping machine.	48 hours steam.	
	20	1 : 2½	do	do	96 hours steam.	
1919 replacement	21	1 : 3	do	Packer-head machine.	Steam	Aggregate up to ½ inch.

[a] Plastic consistency=Damp sand consistency. As wet as would permit immediate removal of the jacket. Quaking consistency=Not fluid, but wet enough to require retention in the molds for several hours. Fluid consistency=Soupy mixture which was easily poured from a bucket.

II. EARLY HISTORY OF FIELD INVESTIGATION PRIOR TO 1919

1. PROGRAM AND SCOPE OF DRAIN TILE INVESTIGATION

This field investigation, started in 1913, was the outcome of a laboratory investigation started in 1908 by the technologic branch of the U. S. Geological Survey to determine the effect of alkali waters and sea water on cements and concretes. These investigations were transferred by act of Congress to the Bureau of Standards in 1910, and the results were published in 1912.[1] Briefly, these investigations showed that practically all cements are attacked by alkali water upon exposure in the laboratory, and complete disintegration may be obtained under certain conditions. Similar investigations have been made by other laboratories with similar results.[2]

As the result of a field survey of structures exposed to alkali waters in the Western States, it was felt that the laboratory investigation should be supplemented with a thorough field investigation in which large-sized test specimens would be exposed to the natural field conditions.

An advisory committee was formed in 1913, composed of representatives of Drainage Investigations, Department of Agriculture, the Reclamation Service, Department of the Interior, the American Association of Portland Cement Manufacturers, and the Bureau of Standards. This committee has since been enlarged, in 1919, by the addition of members representing the Portland Cement Association, the American Concrete Pipe Association, and the Engineering Institute of Canada.

A program was drawn up which provided for the manufacture of 16 varieties, or types, of cement drain tile, 8 inches in diameter and 12 inches long, to be installed in working drains in the Western States. To replace tile removed for test, five additional types have since been provided for installation in the drains at intervals, as listed in Table 1.

A list of all drain tile provided for test, as well as essential data relating to their manufacture, are included in Table 1. The tile of the original series were manufactured during the summer of 1913 at a commercial cement tile plant at Armstrong, Iowa. Good practice was followed in the manufacture of these tile and

[1] B. S. Tech. Paper, No. 12, Action of Salts in Alkali Water and Sea Water on Cements.

[2] Montana State Agricultural College, Circular No. 8, 1910; Bulletin No. 81, 1910. Colorado Agricultural Experiment Station, Bulletin No. 132.

every precaution was taken to make as good and uniform tile as the proportions of materials used would permit.

After a curing period of at least one month carload shipments were made to each of the following places where they were installed in working drains.

Tile shipped to the following districts were installed in concentrated alkali soils where there was sufficient ground water available in the soil to result in flow during a portion of the year: Garland, Wyo.; Fort Shaw, Mont.; Huntington, Utah; Sunnyside, Wash.; Yuma, Ariz.; Roswell, N. Mex.; Grand Junction and Montrose, Colo.

To obtain comparative test data, shipments were also made to Crookston, Minn., and Columbia, Mo., where the tile would be exposed only to fresh water. Another shipment was made to Iowa State College, Ames, Iowa, for storage in the open, exposed to the atmosphere.

Referring to the tile used in the original installation of 1913, as listed in Table 1, it will be seen that proportions varied from 1 cement–1½ aggregate to 1 cement–4 aggregate. For most series a plastic consistency was employed which was as wet as could be used with the packer-head machine and yet permit the immediate removal of the jacket. The hand-tamped tile were molded in sheet metal forms. Series 2 was molded of a quaking consistency mortar which was sticky and slightly flowable, requiring that the forms be kept in place for several hours. Series 14 and 15 were of a soupy, creamy consistency, which was poured from a bucket. Series 3 to 6, inclusive, were similar as to cement and aggregate content, but received different treatments after molding. Series 4 was dipped in neat cement grout after 24 hours. Series 5 was dipped in hot coal tar pitch after 30 days, while 10 per cent ferrous sulphate by weight was used in the mixing water of series 6. Steam-cured tile were exposed to exhaust steam for a total period of 96 hours. The water-cured tile were held in the curing rooms for a period of 12 days, during which time they were sprinkled twice daily without exposure to steam.

To replace tile removed for test in 1914, series 17 and 18 tile were manufactured and furnished by the Universal Portland Cement Co., Chicago.

Series 19 and 20 tile used for replacement in 1915 were manufactured by the Utah Concrete Pipe Co., Salt Lake City, Utah.

In 1919 tile removed for test were replaced by tile manufactured by the Zeidler Concrete Pipe Co., Muscatine, Iowa, and furnished by the American Concrete Pipe Association.

Locations of the drains and concrete block sites in the Western States are shown in the frontispiece, Fig. 1, and the distribution of the various types of the tile in each drain for convenience of removal for test is shown in Fig. 2.

2. PROGRAM AND SCOPE OF CONCRETE BLOCK INVESTIGATION

To determine the effect of alkali waters on concrete placed above and below the ground line a large number of concrete blocks were molded and installed in 1915. In order that actual field conditions might be duplicated blocks of concrete 10 inches square and 2½ feet long were provided, to be placed vertically, with the lower end embedded in the ground to a depth of 1 foot. Two vertical steel reinforcing rods were placed in each block, 2 inches from each face, and a third rod formed a loop projecting from the top which aided in handling. One series of blocks was molded at Denver, a central point, where an excellent quality of aggregate was available, in order to insure a uniform and good quality of concrete. Representative lots of these blocks were shipped to all projects where tests were to be made. Another series of similar blocks was molded at each project and after curing for 30 days was set in place in the soil, while a third series was molded in place immediately exposed to alkali water. At each project the cement in use there was used and the aggregates were of those then available in commercial quantities near the site of construction work on the projects.

The manufacture of one set of blocks at Denver insured a good quality of concrete which would be installed on all projects, thereby permitting direct comparisons to be made of the severity of alkali action at the block sites of the different projects, as well as to give an idea of the relative qualities of the many concretes made with local materials.

Concrete blocks were manufactured and installed at Orman, S. Dak.; Powell, Wyo.; Fort Shaw, Mont.; Sunnyside, Wash.; Fallon, Nev.; Mesquite, N. Mex.; Montrose and Grand Junction, Colo.

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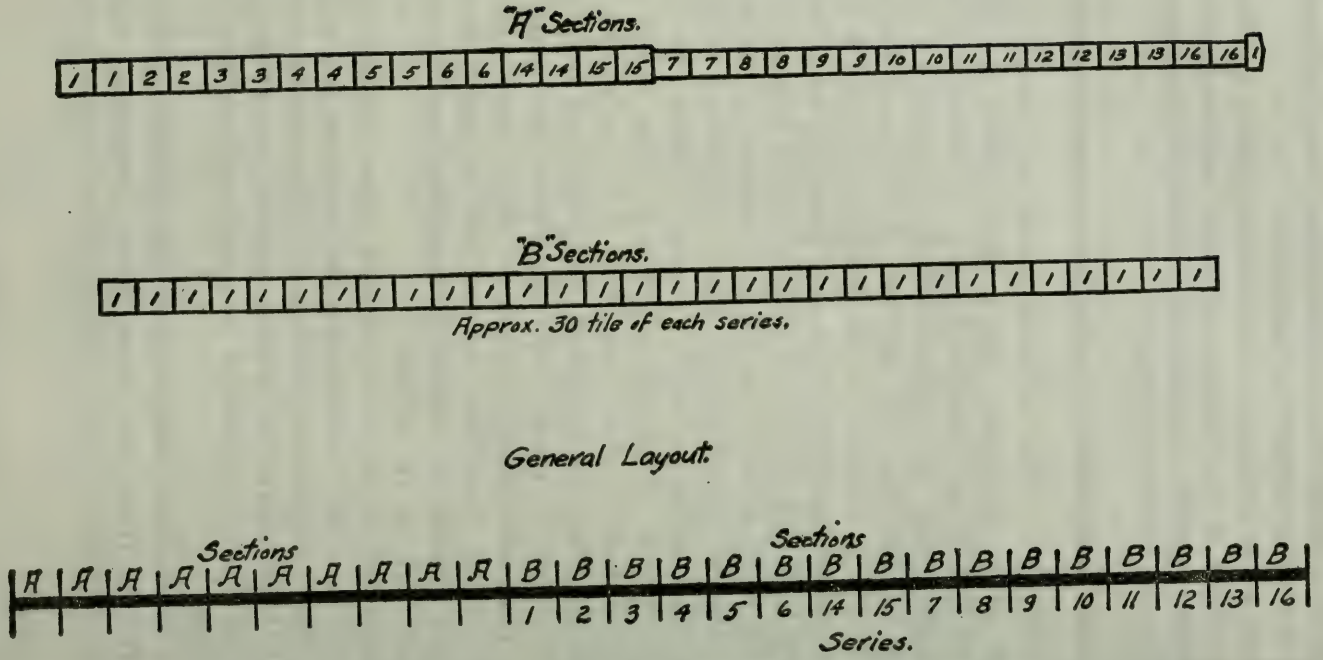


FIG. 2.—*Arrangement of drain tile. The "A" sections contain two tile of each series and were thus arranged for convenience in removal for testing. There are 10 "A" sections followed by "B" sections each of which is composed of all the remaining tile of one type*

In the following table is shown a list of concrete blocks manufactured and installed on each project:

TABLE 2.—List of Concrete Blocks Molded and Installed in 1915

[All blocks molded in smooth wood molds unless otherwise indicated. Blocks are 10 inches by 10 inches square and 30 inches long.]

Place of installation	Molded at Denver: "A" series (proportions by volume)		Molded at project			
			Central yard: "B" series (proportions by volume)		In place in alkali soil: "C" series (proportions by volume)	
	1:1½:3	1:2½:5	1:1½:3	1:2½:5	1:1½:3	1:2½:5
Orman, S. Dak	2	2	2	2	2	2
	[a] 2	[a] 2	.....	.....	.....	.....
	[b] 2	[b] 2	.....	.....	.....	.....
Powell, Wyo	2	2	2	2	2	2
	[a] 2	[a] 2	.....	.....	.....	.....
	[b] 2	[b] 2	.....	.....	.....	.....
Fort Shaw, Mont	2	2	2	2	2	2
Sunnyside, Wash	2	2	2	2	2	2
Mesquite, N. Mex	2	2	2	2	2	2
Fallon, Nev	2	2	2	2	2	2
Montrose, Colo	2	2	2	2	2	2
Grand Junction, Colo.[c]	2	2	2	2	2	2
	[a] 2	[a] 2	.....	.....	.....	.....
	[b] 2	[b] 2	.....	.....	.....	.....

[a] Molded in steel-lined molds.
[b] Molded in rough-wood molds.
[c] Blocks of both proportions of sand cement concrete and natural cement concrete were also molded at Denver for installation at Grand Junction.

Throughout the block work care was taken to produce the best possible quality of concrete. All materials were weighed to insure accuracy and thoroughly mixed by shoveling in batches sufficiently large for a single block. Sufficient mixing water was used to result in a plastic quaking concrete which handled and placed easily. For the Denver blocks equal quantities of water were used for all blocks of the same proportion. The same procedure was followed at each project. The consistency was not fluid as is commonly used in reinforced concrete construction work, and was probably slightly stiffer than could be used in many structures.

With the variations in brands and constituents of Portland cement used and with the different gradations of aggregates available on the different projects, a large variety of concretes were obtained in this manner, all of which are linked up in such a manner that definite conclusions can be drawn for all through the results obtained with the Denver blocks which were installed at all projects. Full records were kept of quantities of cement, sand, gravel, and water used, and samples of each were obtained for complete laboratory tests and analyses.

3. METHODS OF FIELD TESTS AND INSPECTIONS

As indicated in Fig. 2, the tile originally installed were so grouped that excavation of a continuous trench 32 feet long would allow the removal of a section consisting of 2 each of the 16 types. Field tests made in 1914, 1915, and 1916 consisted of the removal of one or more such sections and crushing tests made near the drain by means of a portable hydraulic tile testing machine which was designed and built at the Bureau. Samples of all broken tile were obtained and observation was made as to the condition of each, such as apparent amount of moisture and white salts in the walls. Samples of soils and waters were obtained for chemical analysis. During the early part of the investigation water samples were also obtained for analysis each spring.

The concrete blocks were inspected in 1916 after one year's exposure. This consisted of visual inspection of each block above and below the water or ground line. Samples of soil waters to which the blocks were subjected were secured for chemical analysis.

4. SUMMARY OF RESULTS OF FIELD INSPECTION PRIOR TO 1919

(*a*) DRAIN TILE

The condition of the drain tile after three years' exposure may be summarized briefly as follows:

Since the resistance of the tile to alkali action is found to vary more generally with the consistency of the mixture and the method of manufacture, the following grouping is made for convenience of reference:

(*a*) Plastic consistency, machine-made. Series 8, 12, and 16 (proportions 1:4); 7 and 11 (1:3); 9 and 10 (1:1½); 13 (1:2½); 19 and 20 (1:2½ replacement tile 1915).

(*b*) Plastic consistency, handmade. Series 1 (1:2½); 3, 4, 5, and 6 (1:2).

(*c*) Quaking consistency, handmade. Series 2 (1:2½); 17 (1:1½); and 18 (1:2).

(*d*) Fluid consistency, handmade. Series 14 (1:3) and 15 (sand cement 1:3).

Considering group (*a*), one or more of the tile of each series have been found to contain varying quantities of salts at one or more of the projects. Tile of the proportion 1 part cement to 4 parts sand, plastic consistency (series 8, 12, and 16), have been found in this condition in all drains where exposed to alkali waters, and at 5

of the 8 projects swelling, cracking, and partial disintegration have occurred. Tile made of 1 part cement to 3 parts sand (series 7 and 11), plastic consistency, with a few exceptions, have given no indications in the crushing tests that they have been seriously affected, although alkali salts have been found in the walls of many of the tile, and in one case swelling and cracking were observed.

Tile of group (*b*) have been found generally to contain salts at all projects where exposed to alkali water. In some cases cracking and swelling have been observed. None of these tile are made of mixtures leaner than 1 part Portland cement to 2½ parts sand. The inefficiency of hand tamping of a plastic or dry mixture is clearly shown by these tile. The resistance of these tile to alkali exposure is apparently no greater than that of the leanest mixture of group (*a*). No positively beneficial effects have resulted from the addition and the use of ferrous sulphate in the mixing water of series 6, or by a coating of neat cement grout (series 4), or by a coating of tar (series 5). While the coatings of series 4 and 5 have had some apparent beneficial effects in retarding action in waters of low concentration, the retarding action appears to be negligible where concentrations are high. All tile of these 3 series were made in the proportion of 1 part cement to 2 parts sand.

Of group (*c*), the tile of series 2, quaking consistency, were hand tamped, and those of series 17 (1 part cement to 1½ parts sand) and 18 (1 part cement to 2 parts sand) were made on a jigging device. No salts have been found in the interior of the walls of these tile when tested, but one tile of series 17, at Roswell, and one tile each of series 17 and 18, at Montrose, were attacked and disintegrated on the outer surface in contact with the soil. With few exceptions, these tile when tested have appeared dry or wet in spots only in the interior of the walls. The tile of series 2 (1 part cement to 2½ parts sand, quaking consistency) are the only tile which have to date (1916) shown no disintegration nor alkali salts in the walls at any of the projects where exposed to alkali waters.

In group (*d*) are included series 14 (1 part Portland cement to 3 parts sand, fluid consistency) and series 15 (1 part sand-cement to 3 parts sand, fluid consistency). The sand cement tile have shown alkali salts in the pores, and in numerous cases have shown a softening of the wall at several of the projects, which action was

first noted at Montrose in 1914, when the first years tests were made. Series 14, most nearly comparable with series 2 group (*c*) in quality, has usually been found dry, or damp only in spots when tested. A small amount of alkali was visible in the end of one tile each of series 14 at Montrose and Grand Junction in 1916.

Nothing has been found in the results of tests or the appearance of the tile at Crookston, exposed to fresh water, which would indicate any harmful constituents in the soil or water.

While many of the individual tile in fresh water at Columbia, Mo., showed an increase in strength over the results of previous tests, all tile excepting series 17 to 20, which have been exposed only 2 years and 1 year, respectively, and series 5, tar coated, showed evidences of disintegration on the lower, outer surface, indicated by the apparent dissolving away of cement, leaving the sand grains coated with a brown stain. This action was in every case confined to the outer ⅛ circumference in direct bearing on the bottom of the trench. The other portions of the tile were apparently unaffected. While the tile of the 1:4 proportions (series 8, 12, and 16) were in some cases badly pitted, the richer and denser tile showed only slight surface action.

The condition of the tile removed from section 5 at Columbia in 1919 is shown in Fig. 3. The tile of series 3, most seriously affected, is of the plastic, hand-tamped type, while series 2, apparently only slightly affected on the surface, is representative of the best quality. The tar coating of the series 5 tile has been penetrated.

While results of crushing tests are of some value in indicating durability in alkali soils, a visual inspection of the crushed tile offers a better means of measuring the result of exposure to such conditions.

(*b*) CONCRETE BLOCKS

After one year's exposure none of the 1:1½:3 proportion blocks molded at Denver with selected aggregates (series "A") have shown signs of disintegration on any of the projects. The 1:2½:5 proportion blocks have also been unaffected with the exception of those installed at Fort Shaw and Grand Junction.

It is noticeable that the "C" series blocks made with local aggregate and molded in place exposed to alkali waters are in better condition than the "B" series blocks made of the same materials but placed in the ground after 28 days curing at Orman, S. Dak., Fort Shaw, Mont., Mesquite, N. Mex., Montrose, and

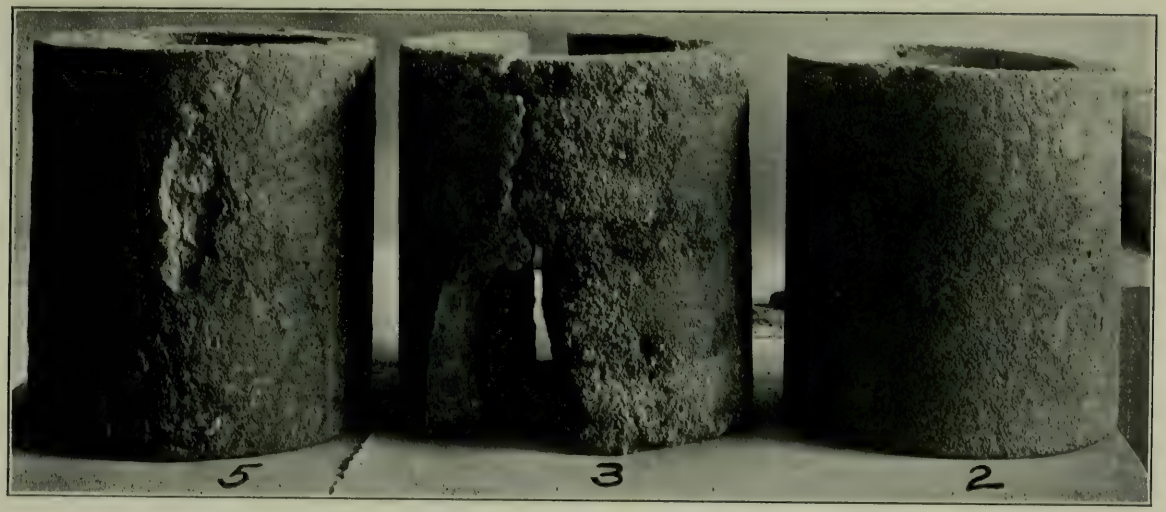


FIG. 3.—*Tile removed from drain at Columbia, Mo., in 1919, affected apparently by acid action*

The tar coating of series 5 had been penetrated as shown. The uneven tamping of handmade tile is shown by the appearance of the rings. A hole was easily scraped through the wall of this tile. The only apparent effect on the series 2 tile is the erosion and roughening of the surfaces, exposing sand grains.

Grand Junction, Colo. At Powell, Wyo., the reverse condition is found, the "C" series blocks having been slightly affected while the "B" series blocks were in good condition. Three of the four sand-cement blocks installed at Grand Junction were slightly scaled and pitted, while the fourth, a 1:2½:5 proportion made so dry that a rough appearing block resulted, was apparently unaffected.

Natural cement blocks were entirely disintegrated at Grand Junction 3 months after being installed. Low temperatures no doubt aided in this rapid action.

TABLE 3.—Individual Results of Crushing Tests of Experimental Cement Drain Tile, 1919

[Total breaking load in pounds. See B. S. Tech. Paper, No. 95, for previous tests.]

Series No.	Result after exposure to atmosphere: [a]Ames, Iowa	Results after exposure to fresh water at—				Results after exposure to alkali water—											
		Columbia, Mo.		Crookston, Minn.		Garland, Wyo.		Fort Shaw, Mont.		Sunnyside, Wash.		Yuma, Ariz.		Roswell, N. Mex. Sec. 5	Montrose, Colo. Sec. 5	Grand Junction, Colo. Sec. 5	Huntington, Utah Sec. 5
		[b] Sec. 5	[b] Sec. 6	Sec. 5	Sec. 6	Sec. 5	Sec. 6	Sec. 5	Sec. 6	Sec. 5	Sec. 6	Sec. 5	Sec. 6				
1a	3850	[*] 1770	2330	2950	3000	[c] 3430	[c] 3490	[c] 3330	[c] 2860	[c] 2670	[d] 2050	[c] 2930	[c] 3070	[c] 2750	[d] 3110	[d] 2340	[c] 2900
1b	3850	2580	2350	3590	3500	[c] 3290	[c] 2270	[c] 3280	[c] 2940	[c] 3060	[c] 3160	[c] 3060	[c] 3270	[c] 2900	[c] 3830	[d, e] 0	[d] 2130
2a	3370	.....	2330	(f)	3300	[g] 3710	2670	[g] 3260	3170	[g] 3310	[g] 3250	[g] 3370	[g] 3170	3440	4000	[g] 3570	3430
2b	3570	2440	2370	3550	2900	[g] 3500	3090	[g] 3220	3320	[g] 3390	[g] 3740	[g] 3120	[g] 3260	3420	3950	[g] 3370	3370
3a	2940	.....	3000	(f)	2880	[c] 2460	[c] 2860	[c] 2040	.....	[c] 2570	[c] 2530	[h] 2850	[c] 2350	[c] 2790	[d] 1950	[d] 1850	[d] 2400
3b	2370	2780	2280	3190	2970	[c] 2360	[c] 2650	[c] 2670	[c] 2190	[c] 3250	[c] 2050	[c] 2800	[c] 2480	[c] 3080	[d] 1800	[d, e] 0	[d] 2030
4a	3820	2910	2250	2890	2675	[c] 2680	[c] 2460	[c] 2130	[c] 2970	[c] 2650	[c] 2750	[c] 2880	[c] 3450	[c] 3230	[c] 3050	[d] 2700	[d] 2180
4b	3620	2340	1990	2600	2600	[c] 2830	[c] 2830	[c] 2600	[c] 3150	[d] 2230	[d] 2600	[c] 3100	[c] 2900	[c] 2650	[c] 3400	[d] 1290	[d] 2400
5a	3050	.....	2250	3600	(i)	[c] 2860	[g] 2700	[c] 2410	[c] 2750	[h] 3010	[c] 2770	[c] 3320	[c] 2920	[c] 2810	[c] 3100	[c] 2220	[c] 3190
5b	2330	2120	2050	3600	3400	[c] 2420	[g] 2990	[c] 2900	[c] 2610	[c] 2710	[c] 2470	[c] 3180	[c] 2200	[c] 2710	[c] 2780	[c] 2380	[c] 2380
6a	2830	2460	2370	2190	2700	[d] 2110	[c] 2080	[c] 1930	[c] 2260	[c] 2390	[c] 2160	[c] 2330	[c] 1980	[c] 2450	[d] 2800	[d, e] 0	[d] 1070
6b	3150	2060	1900	2650	2650	[d] 2840	[c] 2280	[c] 2700	[c] 2470	[c] 2700	[c] 2850	[c] 2920	[c] 2350	[c] 3150	[c] 2840	[d] 2600	[d] 550
14a	3130	1900	1680	3600	3600	[g] 2840	[g] 3140	2520	2730	[g] 2600	[g] 3350	[g] 2830	[g] 3180	[g] 2800	3700	[g] 3140	2680
14b	2950	2000	2180	3900	2950	[g] 3050	[g] 2420	2570	2700	[g] 3320	[g] 2970	[g] 3120	[g] 3410	[g] 3150	3940	[g] 3200	2780
15a	2080	1500	1320	2200	(f)	[h] 2030	[h] 1470	[c] 1720	[c] 1420	[h] 1540	[d] 1540	[h] 2170	[g] 1720	[h] 2060	[d] 800	[d] 1350	[c] 1720
15b	2160	[i] 940	1520	1300	(f)	[h] 1710	[h] 1930	[c] 1610	[c] 1640	[h] 1720	[d] 1540	[h] 1850	[g] 2100	[h] 2000	[d] 1150	[d] 1290	[c] 2200
7a	1620	990	850	(f)	(f)	[c] 1320	[g] 1010	[c] 1240	[c] 1190	[c] 1130	[c] 1130	[c] 1490	[h] 1100	[c] 1240	[g] 1740	[c] 1440	[d] 1170
7b	1540	1010	1020	1175	1440	[c] 790	[g] 1120	[c] 1310	[c] 1650	[c] 1000	[c] 1120	[c] 1480	[c] 1480	[c] 1000	[c] 1240	[c] 1290	[d] 1110
8a	940	850	680	(f)	590	[c] 1000	[c] 1040	[c] 1100	[c] 1100	[d] 760	[c] 980	[c] 1190	[c] 1180	[c] 1260	[d] 600	[c] 1180	[d] 680
8b	1130	640	690	(f)	800	[c] 770	[c] 830	[c] 970	[c] 1190	[c] 940	[c] 1070	[c] 1000	[c] 1160	[c] 1170	[c] 1060	[c] 950	[c] 950
9a	1900	1280	1290	(f)	1350	[c] 1820	[c] 1620	[c] 1410	[c, i] 1300	[g] 2070	[g] 1770	[c] 2270	[c] 1780	[c] 1400	[c] 1800	[g] 1850	[g] 1300
9b	2000	1180	1200	(f)	775	[g] 1610	[g] 1580	[c] 1600	[c] 1730	[g] 1900	[g] 1660	2070	[c] 1390	[c] 1850	[g] 1650	[c] 1710	[g] 1780
10a	1840	1090	1340	(f)	840	[g] 1610	[g] 1620	[g] 1600	[c] 1830	[g] 1560	[g] 1950	[c] 1640	[c] 1450	[c] 1810	[c] 1750	[c] 1670	[c] 1200
10b	1750	980	1170	[i] 925	1140	[c] 1620	[g] 1350	[g] 1400	[c] 1600	[g] 1570	[g] 1810	[c] 1570	[c] 1900	[c] 1350	[g] 1240	[c] 1670	[g] 2010
11a	1650	1070	1080	1150	875	[c] 1440	[g] 1550	[c] 1170	[c] 1350	[c] 1230	[g] 1470	[c] 1400	[c] 1450	[c] 1430	[g] 1540	[c] 1420	[g] 1410
11b	1770	1170	1120	1300	500	[c] 1250	[g] 1300	[g] 1340	[c] 1520	[g] 1460	[h] 1280	[c] 1450	[c] 1450	[c] 1580	[c] 1120	[h] 1280	[c] 1370
12a	1300	780	830	1000	450	[c] 1020	[c] 820	[i, c]	[c] 1170	[h] 1000	[c] 850	[c] 1250	[c] 1020	[c] 1040	[d, e] 0	[c] 1060	[c] 1100
12b	1600	760	930	1190	400	[c] 1010	[c] 920	[c] 1130	[c] 1060	[d] 550	[c] 1200	[c] 1160	[c] 1020	[c] 1330	[d] 670	[c] 1280	[c] 1070
13a	1700	1190	[i] 750	2000	740	[g] 1250	[g] 1600	[c] 1440	[c] 1490	[g] 1600	[g] 1470	[c] 1570	[c] 1340	[c] 1450	[d] 1250	1690	[g] 1630
13b	1500	1070	1320	1220	690	[g] 1710	[c] 1510	[c] 1280	[g] 1600	[g] 1390	[g] 1770	[c] 1590	[c] 1350	[c] 1550	1540	[c, e] 1060	[g] 1700

16a	1640	1000	680	1100	(f)	c 1120	c 1850	c 1310	c 1130	c 1240	c 1220	c 1200	c 1220		c 1020	d, e 0	d, e 0	c 1270
16b	1400	920	740	1000	650	c 580	c 1000	c 1230	c 1300	c 1210	c 870	c 1190	c 1300		c 930	d, e 0	d, e 0	c 1080
17a	1660	1050	.....	(f)	.....	g 1780	.....	g 1680	.....	g 1750	.....	g 1630	.....		f 1540	f, e 0	1810	1420
17b	2000	1250	.....	(f)	.....	g 1690	.....	i 1180	.....	g 1650	.....	g 1400	.....		f 1340	f, e 0	1450	i, c 1130
18a	1780	1120	.....	(f)	.....	g 1520	.....	g 1880	.....	g 1520	.....	g 1520	.....		1550	f 1480	1550	g 1110
18b	1850	1060	.....	(f)	.....	g 1600	.....	g 1730	.....	1380	.....	g 1700	.....		f 1320	f, e 0	1550	g 1220
19a	2220	1430	1370	2000	(f)	g 1690	g 1710	c 1740	.....	c 1610	g 1680	c 1550	c 1780	g 1560	1620	1950	1600	c 1680
19b	2060	1490	1440	2250	(f)	g 1920	g 1680	g 1700	.....	g 1580	g 1430	c 1840	c 1930	g 1620	g 1650	2070	c 1550	c 1720
20a	2050	1370	1320	1630	1850	g 1780	g 1720	g 1690	.....	g 1650	g 1540	c 1740	c 1700	g 1530	g 1680	1870	1700	c 1530
20b	1620	1610	1250	1700	1690	g 1850	1690	g 1520	.....	g 1540	g 1480	c 1600	c 1780	g 1400	g 1550	1890	1750	c 1400

a Stored in warm dry room for two months previous to test.
b Disintegration in evidence on all tile of series 1 to 20. See page 62, B. S. Tech. Paper, No. 95. Some action noted in 1919 on tar-coated series 5.
c Moisture and alkali apparent in fractured surfaces. No cracking, swelling, or disintegration apparent.
d Saturated; large amount of alkali; cracked; disintegrated.
e Swollen; cracked; broken in removal from drain. Considered as "0" in strength averages.
f Cracked, longitudinally, apparently by freezing of water in drain while full.
g Damp; wet spots in fractured surfaces.
h Saturated; entire face of one or more fractured surfaces wet.
i Old crack in wall; probably there when tile was installed.
j Disintegration evidenced by presence of salt and swelling just inside outer surface. See Fig. 4. Fractured surfaces appear dry.

TABLE 4.—Average Results of Crushing Tests of Experimental Cement Drain Tile on 8 Alkali Projects, 1919

[See individual test results in Table 3. See B. S. Tech. Paper No. 95 for previous test results.]

Place of exposure to alkali water.	Average results for series No. —																				Average all series.
	1	2	3	4	5	6	14	15	7	8	9	10	11	12	13	16	17	18	19	20	
Garland, Wyo	3120	3240	2580	2700	2740	2235	2860	1785	1060	910	1655	1550	1385	940	1520	885	1735	1560	1775	1760	1900
Fort Shaw, Mont	3100	3240	2275	2710	2665	2340	2630	1545	1345	1090	1510	1605	1345	1120	1455	1242	1680	1805	1720	1605	1900
Sunnyside, Wash	2735	3420	2600	2555	2740	2525	3060	1585	1095	935	1850	1720	1360	900	1505	1135	1700	1450	1575	1550	1900
Yuma, Ariz	3080	3230	2620	3080	2905	2395	3135	1960	1385	1130	1875	1640	1435	1110	1460	1225	1515	1610	1775	1705	2015
Roswell, N. Mex	2825	3430	2935	2940	2760	2800	3025	2030	1120	1215	1625	1580	1505	1185	1500	975	1440	1435	1595	1555	1975
Montrose, Colo	3470	3975	1875	3225	2940	2820	3820	975	1490	830	1725	1495	1330	335	1395	0	0	975	2010	1880	1830
Grand Junction, Colo	1170	3470	925	1495	2300	1300	3170	1320	1365	1065	1780	1670	1350	1170	1375	0	1630	1550	1575	1725	1535
Huntington, Utah	2515	3400	2215	2290	2785	810	2730	1960	1140	815	1540	1605	1390	1085	1665	1175	1275	1165	1700	1465	1735
Grand average, 8 alkali projects	2750	3425	2255	2625	2730	2155	3055	1645	1250	1000	1095	1610	1390	980	1485	820	1370	1445	1715	1655	1850
Maximum individual	3830	4000	3080	3450	3320	3150	3940	2200	1740	1260	2270	2010	1580	1330	1770	1310	1810	1880	2070	1890	.....
Minimum individual	0	3090	0	1290	2200	0	2420	1290	790	600	1300	1200	1120	0	1060	0	0	0	1550	1400	.....

III. FIELD INVESTIGATION OF 1919

1. DRAIN TILE

(a) RESULTS OF INSPECTIONS AND TESTS

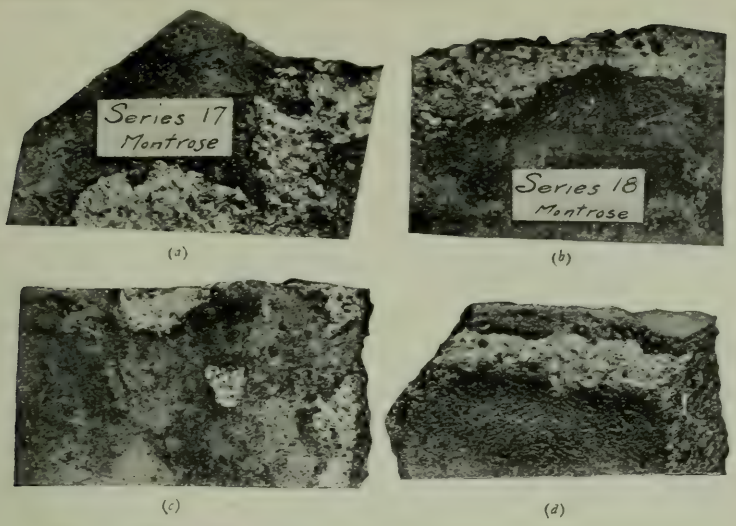
All drains were visited, and tests were made of not less than two tile of each series at each project. Individual results of crushing tests of tile, together with observed quantities of salts in the walls, are shown in Table 3. In Table 4 are shown the average results of crushing tests at each project.

In general, the condition of the tile was quite similar to that found in 1916. Average strength results, as well as appearance of the tile with respect to salts in the walls, had not been greatly changed by the three additional years of exposure.

At Fort Shaw, Mont., there had been no appreciable change in the condition of the tile in the test sections at the upper end, but at the lower end a cave-in in the line indicated more serious and complete cases of disintegration than had previously been found in this drain. The lower end of the drain line lies in low ground on the edge of a shallow lake. Under ordinary conditions the shore of the lake is heavily carpeted with salt. Excavation of the caved-in section showed that the 16 grouped tile of series 15 were entirely disintegrated and collapsed. Two adjacent tile of series 7 were also disintegrated, and the grouped tile of series 14 were found to have considerable quantities of salts in their walls, as evidenced by chipping of the ends during excavation, but none of the series had collapsed. The condition of the tile in this portion of the drain indicates that samples of the drain water taken twice yearly from the upper and lower ends of the line have not been representative of the concentrations which have been present locally in the soil immediately surrounding many of the tile. The upper end of the line lies in boggy ground and normally the entire flow is supplied from this source. The soil surrounding the tile at the lower end is, however, high in soluble salts and generally moist, so that at times these tile may be in contact with relatively high concentrations. Further reference will be made to this condition at Fort Shaw.

Condition of the tile at Roswell showed little change from that of 1916. The tile of series 17 and 18 were again found to have been affected by the same surface disintegration first noted in 1916, as shown in Fig. 4.

At Montrose, as in 1916, series 17 and 18 were found disintegrated, as shown in Fig. 4, except that the action had pene-



(*a*) (*b*) (*c*) (*d*)

FIG. 4.—*Alkali action on tile of wet consistencies (quaking and fluid) at Montrose, Colo., and Roswell, N. Mex., removed from drains in 1916*

(*a*) Series 17, proportion 1-1½, Montrose, Colo.; (*b*) series 18, proportion 1-2, Montrose, Colo.; (*c*) series 17, Roswell, N. Mex.; (*d*) series 14 proportion 1-3, Montrose, Colo.

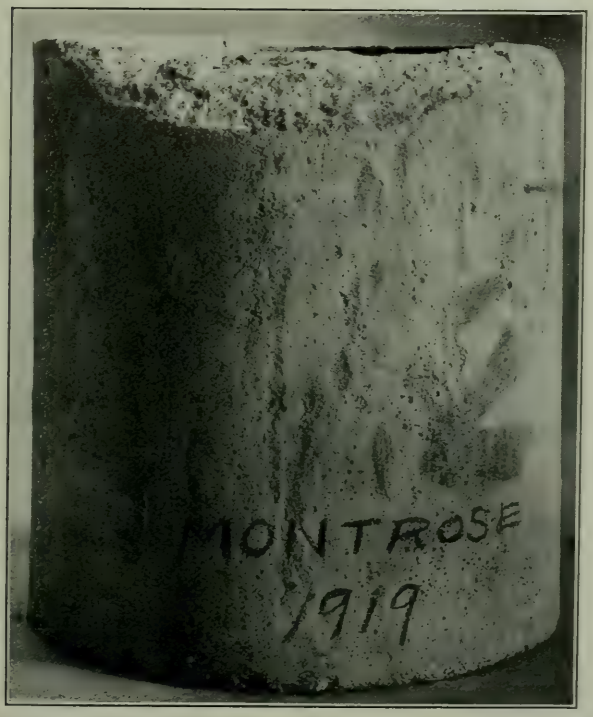


FIG. 5.—*Tile of series 2 removed from the reserve supply in the upper end of the drain at Montrose in 1919*

Four of a total of 12 removed were disintegrated in this manner. Inspection of these tile in 1920 after installation in new drain at Montrose showed the action to be progressing.

trated so far into the walls that 3 of the 4 tile were broken in removal from the drain. The test sections at Montrose are located at the lower end of the drain and the "B" sections, made up of all the surplus tile of each series as shown in Fig. 2, are located at the upper end which was excavated through shale. In removing 12 tile of series 2 from the "B" section for replacement in a new drain a few miles distant, referred to later in detail, it was found that 4 tile had been disintegrated at the ends as shown in Fig. 5. Concentrations found in the drain at Montrose by taking samples at the outlet end have never been high enough to account for this disintegration, and it seems probable that tile placed in the shale are at times exposed to seepage water much higher in concentration than the average of the water flowing through the drain.

It has been noticeable from the beginning of the field tests that the tar-coated tile appear to be most completely saturated of any tile removed from the drains. With very few exceptions the coatings appear to be in perfect condition, both with respect to freedom from alkali action and as to uniformity of coating. Adherence of the tar coat to the concrete surface generally appears to be good, and it is not believed that penetration of this coating by moisture is due to any avoidable defect in the coating.

(*b*) INSTALLATION OF NEW DRAIN NEAR MONTROSE

A new drain was installed northwest of Montrose, near North Mesa Siphon in a small tract of land which has become boggy as a result of seepage of water from higher ground and concentrations of mineral salts from the soil. The concentration of salts in the seepage water at this point is unusually high, about 5 per cent, and advantage was taken of this condition to install a short drain composed of 4 series of experimental tile. These tile were placed in 6 separate sections, each section comprising 2 tile of each of the 4 series, permitting yearly tests for six years. The following series of tile are represented in this drain:

SERIES 21.—1919 replacement tile similar to those installed in all drains after removing the test sections.

SERIES 20.—1915 replacement tile made in Salt Lake City. These tile had been lying in crates at the site of the drain at Grand Junction for four years. No signs of weathering or deterioration were apparent; probably exposure to the weather has increased their resistance to possible alkali action.

SERIES 2.—These tile were removed from the upper end of the drain at Montrose, where they had been in place for six years. As previously mentioned 4 of this group had been disintegrated on the end.

SERIES "A".—Some of the series 21, 1919, replacement tile were treated by soaking in a 5 per cent solution of magnesium fluosilicate for a period of one hour.

(c) INSPECTION OF NEW MONTROSE DRAIN IN 1920

In June, 1920, an inspection was made of the tile placed in the new drain near North Mesa Siphon in December, 1919. One section comprising 2 tile of each series was removed and condition noted as follows:

SERIES 21.—Some disintegration and swelling apparent. Tile had not collapsed.

SERIES 20.—No signs of disintegration or salts in wall.

SERIES 2.—Disintegration, apparent when tile were installed, had made additional progress.

SERIES A.—These tile were swollen, disintegrated, and collapsed. The two tile of the same series in the adjoining section to be removed for inspection at some later date were also completely disintegrated.

These results show (1) marked deterioration for the 1919 replacement tile, series 21; (2) progressive action on the series 2 tile, which have always been found in good condition except in shale at the upper end of the Montrose drain; and (3) no action on series 20 tile, which have occasionally been found with slight amounts of salt in the walls in other drains, but with practically normal crushing strengths. The presence of magnesium fluosilicate, generally used as a concrete hardener and waterproofer, seems to have accelerated disintegration. These limited tests would not be considered as conclusive evidence of the effect of such treatment for exposure to all conditions.

(d) CHEMICAL TEST DATA

For convenience in making comparisons, the average results of chemical analyses of water samples taken at the outlet of drains up to 1917 are included in Table 5, with the analyses of water samples secured during the 1919 inspection. Chemical analyses of soils and waters from the new drain at Montrose, near North Mesa Siphon, are shown in Table 6.

Generally, concentrations were lower in 1919 than were found in previous years. Little variation is shown in the relative quantities of the constituents in the water of any drain. One exception is the great increase of calcium content at Montrose in 1919 and decrease in sodium and magnesium.

Comparing the values of Tables 5 and 6 it will be seen that the concentration of the seepage water in the new drain at North Mesa Siphon is far in excess of any concentration ever detected at any of the eight old drains. No doubt the disintegration of series 2 tile at Montrose and the deterioration of series 14 tile at Fort Shaw can only be accounted for by concentrations approaching that found in the new drain.

TABLE 5.—Analyses (Percentage Reacting Values) of Waters in Experimental Drains

[For explanation of reacting values and method of calculation, see B. S. Technologic Paper, No. 95, pp. 37-43]

Location	Per cent soluble solids in water		Percentage reacting values											
			Na		Ca		Mg		Cl		SO_4		CO_3	
	[a]1	[b]2	1	2	1	2	1	2	1	2	1	2	1	2
Garland, Wyo	0.33	0.20	32.0	33.2	10.3	9.8	7.7	7.0	3.2	1.8	40.6	36.6	6.2	11.6
Fort Shaw, Mont	.20	.12	30.6	29.0	6.6	7.4	12.8	13.6	1.6	.7	34.2	25.2	14.2	24.1
Sunnyside, Wash	.40	.24	24.7	20.4	14.0	17.8	11.3	11.8	5.1	6.3	38.1	37.0	5.8	6.7
Yuma, Ariz	.11	.11	23.5	26.3	16.3	12.9	10.2	10.8	15.4	14.2	12.9	17.4	21.7	18.4
Roswell, N. Mex	.46	.49	23.9	25.4	19.4	18.5	6.7	6.1	27.1	28.1	20.0	19.0	2.9	2.9
Montrose, Colo	.50	.23	9.2	.8	15.8	40.6	25.0	8.6	.5	.....	46.0	46.3	3.5	3.7
Grand Junction, Colo	[c].85	[d].33	25.9	25.5	10.1	11.3	14.0	13.2	17.7	16.2	28.7	25.1	1.9	3.5
Huntington, Utah	.30	No flow.	18.3	.....	20.1	...	11.6	.....	1.8	.....	40.8	.....	7.4	.....

[a] 1=average results of analyses, including 1916 inspection.
[b] 2=analyses of samples taken in 1919. Samples taken at outlet.
[c] 1.7 per cent nitrates.
[d] 5.2 per cent nitrates. Concentration unusually low, probably because of flooding of drains of adjacent tract during irrigation at time sample was taken.

TABLE 6.—Analyses of Soils and Waters from New Drain Near North Mesa Siphon, Montrose

[Drain installed and samples taken in 1919]

Sample and location	Per cent soluble solids in soil or water	Percentage reacting values for samples taken in November, 1919						
		Na	Ca	Mg	Cl	SO_4	CO_3	NO_3
Seepage water at outlet	4.80	36.5	1.5	12.0	4.0	43.2	1.1	1.7
Soil—top 6 inches, upper end of line	3.87	26.7	17.7	5.6	2.8	46.6	.6	.....
Soil—bottom trench, upper end of line	6.05	21.8	25.7	2.5	1.6	48.3	.1	.....
Soil—top 6 inches, lower end of line	5.76	25.4	17.7	6.9	2.4	47.3	.3	.....
Soil—bottom trench, lower end of line	7.06	9.1	38.3	2.6	.8	49.0	.2	.....
Seepage water at outlet June, 1920	2.72	30.2	4.0	15.8	6.6	41.7	1.7	Present.

The analyses of a number of soil samples secured in 1919 immediately in contact with tile which were badly disintegrated aid in emphasizing that concentrations to which individual tile may be exposed may be greatly in excess of the average concentrations as determined by analyses of water samples taken a short distance below at the outlet. These results are shown in Table 7. The analyses of the three soil samples from locations only a few feet apart, at Fort Shaw, illustrate the wide differences in salt content which may be found. The presence of over 5 per cent soluble salt in the soil immediately above a tile is certain to result in high concentrations when sufficient seepage water is present. These results indicate how greatly the salt content of the soil varies only a few feet apart, and are of especial value in pointing out how misleading the analyses of a single sample may be.

TABLE 7.—Analyses (Percentage Reacting Values) of Soils and Alkalies from Tile Drains, 1919

Project	Material and location of sample	Per cent soluble solids in sample	Percentage reacting values					
			Na	Ca	Mg	Cl	SO_4	CO_3
Fort Shaw, Mont.	Soil under tile of series 7, at cave-in at lower end of line	3.15	2.6	42.5	4.9	.....	48.9	1.1
	Soil 6 inches below surface at series 14 and 15, where serious disintegration occurred	1.26	19.2	11.5	19.3	.....	46.5	3.4
	Soil, same location just above tile	5.74	4.4	42.5	3.1	.....	49.5	.6
	Alkali on surface of ground, same location	.....	31.2	4.4	14.1	0.6	49.2	.2
Sunnyside, Wash.	Soil—4 inches to 6 inches below ground surface	2.12	22.7	19.1	8.2	4.7	44.3	1.0
	Soil—below tile in drain	.16	35.7	11.6	2.7	.....	6.9	43.1
	Alkali on surface of ground	.....	37.1	1.4	11.5	6.3	43.5	.2
Roswell, N. Mex.	Soil—bottom of trench	5.82	17.0	30.2	2.8	9.0	38.9	2.1
	White deposit in soil	13.37	3.4	45.9	.7	.8	49.0	.2

2. CONCRETE

(a) RESULTS OF INSPECTION

To give an idea of the change in conditions of the concrete blocks taking place after inspection in the fall of 1916, the results of inspections of that year are included with those of 1919 in Table 8.

TABLE 8.—Condition of Concrete Blocks Molded and Placed in 1915. Results of Inspections in 1916 and 1919

Project	Block number[a]	Proportion	Condition in 1916	Condition in 1919
Orman, S. Dak.[b]	1 A	1:1½:3	Good	Good
	2 A	1:1½:3	do	Do.
	3 A	1:1½:3	do	Do.
	4 A	1:1½:3	do	Do.
	5 A	1:1½:3	do	Slight disintegration ¼ inch deep, one side at ground
	6 A	1:1½:3	do	Good
	32 A	1:2½:5	do	Disintegration ¼ inch deep all sides up to 8 inches from ground
	33 A	1:2½:5	do	Same as 32
	34 A	1:2½:5	do	Corners disintegrated at ground line
	35 A	1:2½:5	do	Disintegrated through at ground line
	36 A	1:2½:5	do	Slight disintegration all sides to top exposing gravel
	37 A	1:2½:5	do	Same as 36
	120 B	1:1½:3	Disintegrated 8 inches up above ground, swollen. Concrete soft	Disintegrated through at ground line
	121 B	1:1½:3	Not so bad as 120. Disintegration extends up 2 inches above ground	Disintegration 2 inches deep all sides at ground line
	122 B	1:2½:5	Surfaces shelled off 8 inches above ground. Concrete at ground soft	Complete disintegration. Pile of gravel remains
	123 B	1:2½:5	Same as 122	Same as 122
	219 C	1:1½:3	Pitting of surfaces at ground. Concrete is hard	Two sides disintegrated ½ inch deep up 8 inches from ground
	220 C	1:1½:3	Pitted at ground showing aggregate slightly worse than 219	Same as 219
	222 C	1:2½:5	Pitting and shelling 2½ inches deep. Soft at water level	Complete disintegration
	223 C	1:2½:5	Disintegration more advanced than 222	Disintegration through at ground line
	301 B	1:1½:3	Molded in 1916	Disintegration 2 inches deep, all sides at ground
	302 B	1:1½:3	Washed sand and gravel	Good
Powell, Wyo.	7 A	1:1½:3	Good	One surface scaled above water line
	8 A	1:1½:3	do	Slight surface scaling above waterline
	9 A	1:1½:3	do	Slight scaling, exposing sand grains up 6 inches
	10 A	1:1½:3	do	Heavy shelling of surface one side to top, exposing large aggregate
	11 A	1:1½:3	do	Slight surface scaling
	12 A	1:1½:3	do	Good
	38 A	1:2½:5	do	Two surfaces badly shelled off to top
	39 A	1:2½:5	do	Same as 38, slightly worse
	40 A	1:2½:5	do	Very slight surface scaling.
	41 A	1:2½:5	do	Heaving shelling off 2 sides to depth of ½ inch
	42 A	1:2½:5	do	Shelling ½ inch deep, all sides to top
	43 A	1:2½:5	do	Surfaces scaled to 6 inches of top
	101 B	1:2½:5	do	Shelling ½ inch deep at water line
	102 B	1:2½:5	do	Slight surface scaling above waterline
	103 B	1:1½:3	do	Good
	104 B	1:1½:3	do	Do.
	201 C	1:1½:3	do	Slight surface scaling 2 inches to 3 inches above water line
	202 C	1:1½:3	Very slight surface pitting above water line	Slightly worse than 201
	203 C	1:2½:5	Considerable scaling of surfaces at water line	Surfaces shelled to depth of 1 inch; large aggregate exposed
	204 C	1:2½:5	Same as 203	Same as 203
Fort Shaw, Mont.	19 A	1:1½:3	Good	Good.
	20 A	1:1½:3	do	Do.
	50 A	1:2½:5	Some surface pitting exposing sand grains	All surfaces scaled to top
	51 A	1:2½:5	Same as 50	Not so bad as 50
	107 B	1:1½:3	Good	No scaling. One corner spalled off at water line
	108 B	1:1½:3	do	Good

[a] "A" designates blocks molded at Denver. "B" designates blocks molded at project with local materials and cured for one month before installation in soil. "C" designates blocks molded at project and exposed immediately to seepage water.

[b] Small cracks apparent on top of all blocks radiating out from steel at top.

TABLE 8.—Condition of Concrete Blocks Molded and Placed in 1915. Results of Inspections in 1916 and 1919—Continued

Project	Block number	Proportion	Condition in 1916	Condition in 1919
Fort Shaw, Mont. (Con.)	109 B	1:2½:5	Some surface pitting and scaling at water line	Heavy shelling, all surfaces exposing stones. Corners spalled
	110 B	1:2½:5	Not so bad as 109	Not so bad as 109
	207 C	1:1½:3	Good	Good
	208 C	1:1½:3	do	Do.
	209 C	1:2½:5	do	Do.
	210 C	1:2½:5	do	Do.
Sunnyside, Wash.	21 A	1:1½:3	do	Slight shelling of surfaces at ground line
	22 A	1:1½:3	do	Same as 21
	52 A	1:2½:5	do	Same as 21 exposed deep and higher on block
	53 A	1:2½:5	do	Same as 21
	1S B	1:2½:5	do	Surfaces shelled ¼ inch to ⅜ inch deep at ground line extending up 4 inches
	2S B	1:2½:5	do	Slightly worse than 1S
	3S B	1:1½:3	do	Same as 21
	4S B	1:1½:3	do	Do.
Fallon, Nev.	27 A	1:1½:3	do	Good
	28 A	1:1½:3	do	Do.
	58 A	1:2½:5	do	Do.
	137 B	1:1½:3	do	Do.
	138 B	1:1½:3	do	Do.
	140 B	1:2½:5	do	Do.
	141 B	1:2½:5	do	Do.
	237 C	1:1½:3	do	Do.
	238 C	1:1½:3	do	Do.
	240 C	1:2½:5	do	Do.
	241 C	1:2½:5	do	Do.
Mesquite, N. Mex.[a]	23 A	1:1½:3	do	Split by large cracks down sides
	24 A	1:1½:3	do	Split by large cracks, swollen surfaces badly shelled
	54 A	1:2½:5	do	Upper portion badly cracked, some swelling
	55 A	1:2½:5	do	Top sloughed off, worse than 54
	143 B	1:1½:3	Slight scaling of surfaces	Split by cracks, some swelling
	144 B	1:1½:3	Same as 143	Same as 143, cracks smaller
	147 B	1:2½:5	Surfaces scaled 4 inches above ground line exposing sand grains	Large cracks in tops and sides. Top sloughed off
	146 B	1:2½:5	Same as 147	Many large cracks. Lumps of concrete easily broken out
	243 C	1:1½:3	Slight scaling of surfaces. Less than 143	Large aggregate exposed, deep pitting. Small cracks in top
	244 C	1:1½:3	Same as 243	Same as 243, not so bad
	246 C	1:2½:5	do	Large aggregate exposed, sounds hollow when tapped
	247 C	1:2½:5	do	Same as 246
Montrose, Colo.	25 A	1:1½:3	Good	Good
	26 A	1:1½:3	do	Do.
	56 A	1:2½:5	do	Surfaces scaled up to 5 inches of top.
	57 A	1:2½:5	do	Same as 56, except deeper
	125 B	1:1½:3	Surface scaled up to 3 inches of top, exposing fine aggregate	Same condition as in 1916
	126 B	1:1½:3	Worse than 125	Do.
	128 B	1:2½:5	Similar to 125	Heavy shelling ½ inch deep at ground line extending 3 inches up
	129 B	1:2½:5	Worse than 125	Shelling off of surfaces 1 inch deep up to top of block
	225 C	1:1½:3	Good	Good
	226 C	1:1½:3	do	Do.
	228 C	1:2½:5	Surfaces scaled to height of 1 inch, exposing small aggregates	Same as in 1916
	229 C	1:2½:5	Same as 228	Same as in 1916; corners spalled

[a] In 1919 all blocks in this group were badly affected by alkali.

TABLE 8.—Condition of Concrete Blocks Molded and Placed in 1915. Results of Inspections in 1916 and 1919—Continued

Project	Block number	Proportion	Condition in 1916	Condition in 1919
Grand Junction, Colo.[a]	13 A	1:1½:3	Good	Good
	14 A	1:1½:3	do	Do.
	15 A	1:1½:3	do	Do.
	16 A	1:1½:3	do	Do.
	17 A	1:1½:3	do	Very slight scaling one side
	18 A	1:1½:3	do	Good
	44 A	1:2½:5	Slight surface scaling up 6 inches, exposing sand grains	Heavy scaling all surfaces 10 inches up
	45 A	1:2½:5	Same as 44	Same as 44
	46 A	1:2½:5	Good	Do.
	47 A	1:2½:5	do	Do.
	48 A	1:2½:5	do	Not so bad as 44
	49 A	1:2½:5	do	Same as 48
	63 A	1:1½:3	One surface scaled 6 inches up from ground	Deep pitting on 3 surfaces
	64 A	1:1½:3	Same as 63	Not so bad as 63
	65 A	1:2½:5	Heavy scaling to depth of 1 inch on three sides	Heavy shelling from ground to top
	[b] 66 A	1:2½:5	Good	Heavy shelling and pitting 1 inch deep at ground, not so bad as 65
	131 B	1:1½:3	do	Good
	132 B	1:1½:3	do	Do.
	134 B	1:2½:5	Heavy shelling ¾ inch deep all sides	Heavy shelling ¾ inch deep, up 4 inches from ground
	135 B	1:2½:5	Same as 134, not so bad	Same as 134. Worse condition
	303 B	1:1½:3	Molded in 1919	Good
	304 B	1:1½:3	do	Do.
	305 B	1:2½:5	do	Do.
	306 B	1:2½:5	do	Do.
	231 C	1:1½:3	Good	Good. Large cracks in top and 8 inches down one side, do not radiate from steel
	232 C	1:1½:3	do	Good
	233 C	1:2½:5	do	Do.
	234 C	1:2½:5	do	Do.

[a] Seepage during past three years has not been sufficient to keep soil saturated to desired extent.
[b] Blocks 67 and 68, natural cement, proportions 1:1½:3, were installed in 1915 and completely disintegrated before the following spring.

In general, blocks which were affected in 1916 were more seriously affected in 1919, the action having been progressive. Due to changes in conditions of exposure at the various projects the rate of disintegration has, in some cases, been very marked, and in others little apparent change has taken place in the 3-year period.

Disintegration is usually first evidenced by a scaling of the neat cement film on the surfaces of a block at and just above the ground line, exposing sand grains. Further action results in exposing particles of the coarse aggregate, giving the block the appearance of having been subjected to erosion. Later, spalling of larger chunks of concrete will be apparent, and if the level of the soil water is at or above the ground surface the concrete may become soft and mushy. The softening and spalling of the surfaces is often accompanied by the formation of large cracks radiating out from the handle steel. The totally embedded bars may also contribute to the failure of the block by corrosion and the resulting

expansion. The disintegrating action is not, however, always confined to the concrete above the surface where evaporation is high, but the lower portion of the block, which is probably always moist, may be equally affected.

No doubt the rapidity of disintegration is in some cases, especially on the northern projects, aided by extreme weather conditions, but the extent of such action can not be definitely determined. The scaling of the neat cement film, the first step in disintegration, were action to proceed no further, might be explained as due entirely to freezing weather and temperature changes, yet even where extreme cold occurs it appears that this may be only a contributing factor and that salt in solution is the primary cause of the trouble. That such scaling may occur without freezing weather was demonstrated at Montrose in 1916. The blocks were installed in the fall of 1915 after water had been turned out of the adjacent canal, so that the water level during the winter was below the ground surface. In the spring the amount of seepage was sufficient to flood the ground surrounding the blocks to a depth of more than 1 foot, the water level standing slightly below the tops. Inspection in the fall of the same year showed that the surfaces of many of the blocks had been badly scaled, the action being apparent up to the water level reached during the summer. Scaling of surfaces is also very apparent at Powell where the water level varies considerably, often standing as high as the tops of the blocks. Concrete structures made of the same materials as the B and C series blocks exposed to the same climatic conditions in a near-by fresh-water reservoir at Powell are in good condition and show no signs of surface action.

In describing the condition of the blocks listed in Table 8, those which have been apparently unaffected in any way have been described as "Good." The numbers of blocks listed as "Good" in 1916 and found to be affected to a greater or less extent in 1919 is most marked at Orman, S. Dak., Powell, Wyo., Sunnyside, Wash., Mesquite, N. Mex., and Grand Junction, Colo. At Fort Shaw, Mont., there has been little change in the three years. Here conditions have apparently been quite uniform ever since the blocks were installed. At Fallon, Nev., none of the blocks have been injured in any manner to date. At Fort Shaw and Sunnyside disintegration has been lacking or confined to surface scaling or pitting, exposing sand and gravel particles. Deeper pitting and disintegration have been noted at Powell, Montrose, and Grand

FIG. 6.—*View of five blocks at Mesquite in 1919 showing cracking and disintegration*

From left to right these blocks are numbered as follows: 143, 147, 146, 54, and 55.

Junction. Serious disintegration of entire blocks has occurred at Orman, S. Dak., and Mesquite, N. Mex. The appearance of some of the blocks at Mesquite in 1919 is shown in Fig. 6. From left to right these blocks are numbered as follows: 143, 147, 146, 54, and 55. It will be noted that the top portions of blocks 146 and 55 are badly disintegrated, and the view of block 143 gives some idea of the serious cracking of the mass above the water, showing a step in the disintegration not quite so far advanced as for the first two mentioned. Owing to the drying up of the block site at Grand Junction after the first year as a result of the silting up of the adjacent canal, only slight changes have occurred there since 1916. The quantity of soil water present at Grand Junction since that time has not been sufficient to develop the extreme conditions which the quantity of salts present in the immediate locality would seem to justify. Conditions at Orman have been continuously bad, and several of the blocks have shown apparent signs of deterioration. The blocks at Mesquite had been little affected previous to inspection in 1916, but all may now be considered as complete failures.

Relative severity of exposure conditions at all of the projects can be judged by the condition of the Denver block (A series) at each, since these are of a uniformly high quality of concrete, similar in every respect.

(*b*) CHEMICAL TEST DATA

Chemical analyses of waters to which the concrete blocks have been exposed are included in Table 9. Since conditions are continually changing, the samples obtained at any project are not sufficient to furnish a complete record. There is no certainty that maximum concentrations have been detected at any site by means of the few samples taken. This is especially true for the 3-year period from 1916 to 1919 when field work was suspended.

With the exception of Fallon, all water samples obtained are of the sulphate type. At Fallon the carbonate radical is practically as high as the sulphate, but taking concentration into account it is seen that the carbonate is little higher than in normal waters. No apparent deterioration whatever has occurred in the concrete blocks installed at Fallon.

Most serious disintegration of concrete blocks has occurred at Mesquite and Orman, and the analyses show that concentrations in excess of 3 per cent have been present at least once.

TABLE 9.—Analyses of Surface and Subsoil Waters at Block Sites, 1915 to 1919

Location	Date	Per cent soluble solids in water	Percentage reacting values					
			Na	Ca	Mg	Cl	SO_4	CO_3
Orman, S. Dak..	Fall, 1915	1.46	24.7	3.5	21.8	0.6	47.9	1.5
	Spring, 1916	.93	22.8	9.3	17.9	.1	45.4	4.5
	Fall, 1916	1.36	23.7	21.8	4.5	.5	47.2	2.3
	Fall, 1919:							
	Surface water at site	3.31	18.3	9.4	22.3	.4	46.6	3.0
	Subsoil water above site	.51	10.5	15.4	24.1	.2	45.9	3.9
	From pond below site	.93	18.3	9.4	22.3	.4	46.6	3.0
Powell, Wyo....	Fall, 1915	.81	42.5	4.2	3.3	3.3	41.9	4.8
	Spring, 1916	.70	41.8	4.0	4.2	3.3	41.5	5.2
	Fall, 1916	.67	41.4	4.2	4.4	3.9	39.6	6.6
	Fall, 1919	.41	43.1	3.3	3.6	3.2	38.2	8.6
Fort Shaw, Mont.	Fall, 1915	.40	36.5	2.4	11.1	2.0	47.3	.7
	Spring, 1916	.95	33.0	6.7	10.3	1.7	47.0	1.3
	Fall, 1916	2.44	34.7	2.7	12.6	1.3	47.7	1.0
	Fall, 1919	1.67	32.0	4.7	13.3	2.0	46.3	1.6
Sunnyside, Wash.	Fall, 1915	.22	19.7	13.9	16.4	8.5	36.9	4.6
	Spring, 1916	.22	29.2	7.0	13.8	6.2	41.1	2.7
	Fall, 1916	.22	26.6	6.9	16.5	8.3	47.3	4.4
	Fall, 1919	.23	29.2	6.6	14.2	8.9	35.1	6.0
Fallon, Nev.....	Fall, 1915	.13	44.8	2.4	2.8	9.0	22.7	18.3
	Spring, 1916	.13	46.7	2.1	1.2	8.5	21.2	20.3
	Fall, 1916	.12	46.4	2.7	.9	9.6	22.1	18.3
	Fall, 1919	.10	44.9	2.7	2.4	8.5	21.2	20.3
Mesquite, N. Mex.	Fall, 1915	.86	43.2	5.5	1.3	21.7	29.4	.9
	Spring, 1916	3.02	43.4	3.7	2.9	14.8	34.6	.6
	Fall, 1916	2.64	42.8	4.0	3.2	23.5	25.8	.7
	Fall, 1919	.47	39.4	7.0	3.6	13.0	36.1	.9
Montrose, Colo..	Fall, 1915	1.61	30.3	4.4	15.3	.7	48.0	1.3
	Spring, 1916	1.09	29.5	6.9	13.6	.7	47.0	2.3
	Fall, 1916	1.78	28.4	5.6	16.0	.7	48.6	.7
	Fall, 1919	.65	16.4	17.4	16.2	.4	48.5	1.1
Grand Junction, Colo.	Spring, 1916	2.51	39.3	3.2	7.5	2.2	47.2	.6
	Fall, 1916	.32	30.6	16.6	2.8	.8	46.6	1.6
	Fall, 1919	1.02	45.6	7.3	7.2	1.1	47.5	.9

The great variations which occur at the same time in seepage waters only a short distance from each other is illustrated by the samples obtained at Orman in 1919. Blocks here are placed below a wasteway in soil which is usually moist, due to seepage from a canal. In 1919 a few inches of water stood over the surface of the ground surrounding the blocks. The concentration of salts in this water was 3.31 per cent. Subsoil water obtained a few feet away in the direction of the canal had a concentration of 0.51 per cent, while a large pool below the block site contained 0.93 per cent salt.

These analyses covering the period from the beginning of the investigation permit the statement that concentrations not less than those indicated for each project have occurred at the stated times but give little idea of what maximum concentrations may have been present before or after these samples were taken or may have been present in other locations even a short distance away.

3. SUMMARY OF RESULTS

(a) DRAIN TILE

Durability of cement drain tile for any given concentration appears to vary with richness of mix and consistency. Hand-tamped tile are less resistant to action than machine-made tile made of the same mortars.

Tile made with sufficient mixing water to result in such a consistency that they must be retained in the molds for several hours have proved more durable than richer mix tile of the machine-made type of such a dry consistency that the jacket may be stripped immediately. Results to date have indicated the 1915 replacement tile, series 19 and 20, made with a combination packing and tamping machine of a consistency permitting immediate removal of the jacket, to be more resistant to alkali action than richer mixes of the same consistency made on the packer-head type of machine or by hand. As a class it may be said that wet mix tile have been much less affected by alkali action than dry mix tile.

Inspection of drain tile and concrete structures in other localities where the alkali salts are of the chloride or carbonate types seem to justify the conclusion that these waters are not so severe as waters of the sulphate type which are found in all of our drains in the alkali districts. Results have shown that it is impossible to estimate the maximum concentrations to which tile in the drain may be exposed by analyses of water flowing in the drain. In waters of the sulphate type severity of action appears to vary with the concentration of soluble salts. The number of types of tile affected by alkali varies roughly with concentration of water as determined by analyses of water samples taken at the outlet. In all cases where disintegration of the best quality of tile has occurred samples of the soil immediately in contact with such tile have revealed concentrations much higher than are indicated by the drain water.

To date, one or more marked cases of disintegration have been noted in every type of tile except series 19 and 20. The fact that appreciable quantities of salt have been found in the walls of this type in some cases would indicate that this type has probably not been exposed to the extreme concentrations found for some of the test specimens of series 2, 17, and 18.

(*b*) CONCRETE

The concrete blocks have all been exposed to waters of the sulphate type. Owing to variation and change in ground water conditions at some of the sites, some blocks have not been exposed to the extreme conditions which might be indicated by analyses of surrounding soils. While the Denver "A" series blocks have generally been more resistant to alkali than the blocks molded on the projects, these blocks have been seriously affected where concentrations have been high.

As in the case of drain tile, it may be stated that severity of action on the concrete blocks appears to vary with concentration of soluble salts. While there is no record of the maximum concentrations encountered, conditions have been such on one project that all blocks installed may be considered as complete failures.

With the same aggregates, lean mixtures are more seriously and rapidly affected than rich mixtures. Durability appears to be dependent upon impermeability, which is mainly dependent upon richness of mix and gradation of aggregates.

IV. CONCLUSIONS

While any conclusions drawn from the results of the investigation to date must be considered as tentative, it is believed that the scope of the work, the variety and types of concretes included, together with the widely different exposure conditions have resulted in extending the knowledge of what occurs when such material is exposed to alkali soils and waters. No doubt further extension of this investigation, as well as independent investigation by others who are interested in the use of concrete under such conditions, will result in more detailed conclusions and accurate limitations, but the work to date has consistently emphasized certain precautions which should be observed by anyone using cement under such conditions.

1. CONCRETE

1. Results to date indicate that materials of good quality and proper workmanship are of great importance in the production of concrete which is to be exposed to alkali soils and waters.

2. Action noted on surfaces of concrete blocks of best quality after 1 year exposure in sulphate waters has in most cases been progressive, depending upon conditions of exposure.

3. Extent and rapidity of disintegration in sulphate waters depends upon concentration of salts in waters to which the concrete is exposed.

4. In blocks containing reinforcing rods disintegration appears to be aided and accelerated in some cases by corrosion of embedded steel and consequent cracking of the concrete, as has been observed in some reinforced concrete structures exposed to sea water.

5. Structures placed in alkaline soils or exposed to alkaline seepage waters should be given all possible protection by drainage.

6. Seepage waters and alkaline soil conditions may be encountered which will disintegrate concrete of the best quality, and proper consideration should be given to soil and water conditions and protection by drainage and other means when it is proposed to expose concrete structures to conditions similar to those in which these test blocks have been placed.

7. Alkali salts are not uniformly distributed throughout the soil or large bodies of seepage waters, and it will be difficult to determine in advance the concentrations to which a structure may later be exposed. A systematic scheme for sampling soils will furnish information as to the quantities and types of salts available for solution, while analyses of seepage waters will indicate the concentrations present at the time of sampling. Disintegration is brought about only by those salts which are in solution as indicated by analyses of water samples, while the soil analyses merely represent reserve supplies which may bring about changes in the existing solutions with changing conditions of rainfall, flooding, etc. The problem of drawing conclusions as to the most severe conditions which may occur becomes more difficult when the source of supply of the salt is through underground seepage from some distant point.

8. For the same concentration of soluble salts, and for the same aggregates, resistance of mass concrete to alkali action appears to vary with cement content or richness of mix, within the limits employed in these tests.

2. CEMENT DRAIN TILE

1. The use of concrete tile in soils containing alkali salts of the sulphate type in considerable quantities is hazardous, in view of the fact that the best quality of drain tile has been disintegrated during an exposure of less than six years.

2. Porous or permeable tile, due to the use of lean mixtures, or relatively dry consistencies, are subject to disintegration in sulphate waters of relatively low concentrations.

2. Dense tile of the best quality, exposed to sulphate waters, are under certain conditions subject to disintegration, depending upon concentration of salts in seepage water, and alkali and moisture conditions in the soil immediately surrounding the tile.

4. Disintegration may be manifested in sulphate waters by physical disruption caused by expansion resulting from the crystallization of salts in the pores, *but it is primarily due to chemical action between the salts in solution and the constituents of the cement.* In the case of dense tile of low permeability exposed to sulphate waters, disintegration may occur at or just inside the surface skin and progress into the wall of the tile.

5. A thin outer skin of apparently unaffected concrete is apparent in the case of disintegration of the best quality of tile. While this relatively thin layer may be either immune to attack by salts in solution, or perhaps be very slowly attacked, results indicate that this carbonized coating is not in itself waterproof, and alkali water may pass through this coating into the mass.

6. In sulphate waters with a concrete or mortar of given quality the disintegrating effect seems to vary with the concentration of the solution.

7. Tile made by the process commonly used, which allows the removal of forms immediately after molding, are more susceptible to disintegration where exposed to sulphate soils or waters than are tile made of wetter consistency which requires their retention in the molds for a period of hours.

8. *The use of hand tamped tile of plastic consistency*, such that the jacket can be removed immediately after molding, can not be recommended for use in sulphate soils and waters. Tile of plastic consistency, molded in the packer-head type of machine, are more resistant to alkali action than the hand tamped tile, but the best quality of packer-head machine tile have been affected in waters of high salt concentration.

9. Steam cured tile show no greater resistance to alkali action than tile which are cured by systematic sprinkling with water.

10. Tile made of sand cement have less resistance to alkali action than tile made of Portland cement of the same proportions.

11. The tar coating as used was not effective in preventing the absorption of alkali water into the walls of the tile.

12. The cement-grout coating is not effective in preventing the absorption of alkali water.

13. No advantage was found in introducing ferrous sulphate into the cement mixture. The use of this material resulted in a reduction of the crushing strength of the tile.

14. If cement drain tile are to be used in soils and waters containing 0.1 per cent or more salts of the sulphate type, their installation should be preceded by an examination of subsurface alkali conditions. Decision as to the advisability of using cement drain tile should be based upon thorough examination of subsurface conditions and quality of product which it is proposed to use, and upon a comparison of the data so obtained with the data presented in this report. Such an examination may indicate portions of an area where the use of cement tile should be avoided. Quantities of alkali salt present can be determined by chemical analyses of the soils. Concentrations to which tile may be exposed can be determined by chemical analyses of the ground waters. In drawing conclusions allowance must be made for the constantly changing concentrations of alkali in the seepage water, which at times may differ as much as several hundred per cent in adjacent areas. There can be no assurance that the concentrations found at any time are the maximum to which the tile will ever be exposed. Quality of cement drain tile can best be measured by permeability tests. With other conditions equal, tile of lowest permeability will be the most durable. There appears to be little definite relation between permeability and the related factors of porosity, absorption, and density.

V. APPENDIX A.—ABSORPTION TESTS ON TILE OF SERIES 1 TO 21

The results of absorption tests on samples of the tile in storage at Ames, Iowa, are shown below. These tests were conducted by W. J. Schlick, drainage engineer, Iowa State College, in 1920, using portions of tile remaining after the 1919 crushing tests of the Ames storage tile were completed.

Series number	Crushing strength	Per cent absorption, average of six pieces		Ratio, boiling to immersion	Series number	Crushing strength	Per cent absorption, average of six pieces		Ratio, boiling to immersion
		Standard boiling test	72-hour immersion test				Standard boiling test	72-hour immersion test	
	Pounds					Pounds			
1	3850	11.0	7.3	1.51	11	1710	8.4	6.1	1.38
2	3470	9.1	7.9	1.15	12	1450	10.7	6.6	1.62
3	2655	11.4	9.3	1.23	13	1600	9.7	6.6	1.47
4	3720	10.1	7.2	1.40	14	3040	9.8	8.8	1.11
5	2690	13.2	9.0	1.47	15	2120	11.5	9.8	1.17
6	2990	13.8	8.9	1.55	16	1520	9.7	6.5	1.49
7	1580	8.6	6.0	1.43	17	1830	6.9	6.8	1.01
8	1035	10.7	6.4	1.67	18	1815	6.3	6.5	.97
9	1950	9.4	5.9	1.52	19	2140	6.9	5.3	1.30
10	1795	7.8	5.9	1.34	20	1835	7.4	5.3	1.40
					21	1210	8.5	5.4	1.57

Absorption values were determined by boiling specimens for 5 hours as specified in the A. S. T. M. specification for tests of drain tile and also by immersion for 72 hours in water at room temperature. Generally the value found for immersion is considerably less than for the 5-hour boil. It is worthy of note that the tile of highest impermeability which have shown greatest resistance to alkali action show practically the same quantities absorbed by the two methods. The differences in permeability are in part due to greater cement content in some cases, but generally to the use of a greater quantity of mixing water than is commonly used in the manufacture of drain tile in the packer-head type of machine. It is possible that further study will indicate the *rate* of absorption to be a measure of the durability in alkali waters, within the ranges of consistencies employed in the manufacture of tile and for equal cement contents. The absorption value obtained is alone of little value in indicating quality, since the poorest and best tile have practically the same absorption percentage. These tests suggest that permeability rather than porosity or density may be a criterion of resistance to alkali action.

VI. APPENDIX B.—THE PRESENCE AND DISTRIBUTION OF SALTS IN THE SOIL AND THEIR ACTION ON CEMENT AND CONCRETE.

The foregoing investigation has to date dealt mainly with observation and tests of mortar and concrete specimens in the form of drain tile and concrete blocks which have been exposed to alkali soils and waters in various districts of the West. Such laboratory work as has been carried on has been in connection with physical tests of cement, aggregates, and concrete and mortar test specimens, together with chemical analyses of materials used, and samples of soils, waters, and alkalies to which the

specimens have been exposed. A discussion of the conditions which have brought about the necessity for studies of the effect of alkali on concrete, together with a summary of the results of other investigations, may be of interest.

Long exposure of rocks to the elements has resulted in their disintegration to form soil through which are found distributed the soluble salts of sodium, calcium, and magnesium. Years of rainfall in the humid regions have resulted in the leaching of the greater portion of the soluble salts from the soil, but in the arid and semiarid regions of the West relatively small quantities have been removed except where by irrigation or other means large quantities of water have been available with good natural drainage conditions. The accumulation of these salts in those regions is usually referred to as "alkali deposits." What is known as "white" alkali is usually a mixture of the sulphates and chlorides of sodium, calcium, and magnesium, while "black" alkali, so called because of its tendency to dissolve vegetation or organic matter and stain the surface of the soil a brown or black color, contains a large percentage of sodium carbonate together with smaller amounts of the white alkali. The white alkali is the most widely distributed type, and experience has shown that it is more injurious to concrete.

Disintegration of concrete structures is usually noted, and is most marked, at and just above the ground line and will vary with soil water conditions. Where the alkali water level is constantly below the limits of soil capillarity, disintegration may be entirely confined to portions below the ground surface. Disintegration at or near the surface is, no doubt, accelerated by frost action and alternate wetting and drying, but these effects are only contributory.

The appearance of concrete affected by alkali salts varies with the quality of the concrete, the concentration of the solution, and duration and condition of exposure. With good quality concrete of low permeability the first stage of the action is marked by the flaking or shelling off of the surface skin of neat cement of rich mortar, exposing sand grains and aggregate particles. As the action continues larger aggregate particles are exposed, and the new surface has the appearance of being abraded, and white deposits of salts appear in the pores. (See Fig. 4.) In the last stage the material loses its identity as concrete and appears to be a mixture of aggregate particles distributed throughout a soft, white, puttylike paste. This change may be accompanied by a considerable increase in volume. Disintegration of concrete of low permeability is essentially a surface action which gradually progresses into the mass. In some cases the outer skin appears to be immune to attack, but it does not entirely prevent the penetration of alkali water, which in reacting with the inner portion causes swelling which shatters the surface skin.

Rapidity of penetration of the action is dependent upon permeability of the concrete, and concentration of salt in solution. Chipping away the affected portion will usually reveal concrete just beyond which is apparently unaffected.

In the case of permeable concrete or mortar mixtures of the type commonly used in hand-tamped drain tile or sewer pipe, a somewhat different and more rapid action occurs. The comparative ease of penetration of alkali water through the wall exposes a large volume of cement to the action of the salts and a rapid swelling and increase of volume results, the whole mass finally breaking down to form the typical white puttylike paste.

The deterioration of concrete in alkali soils when first noted and studied was generally ascribed to the use of poor aggregates or improper methods of mixing and placing concrete, and it was believed that disintegration was brought about merely by the crystallization of alkali salts in the pores of the concrete. Since these salts in crystal form occupy a greater volume than in solution, it was thought that the mechanical forces exerted were sufficient to disrupt the mass and fully account for the disintegration noted. If this theory were true, disintegration could be avoided by producing concrete of low permeability which would prevent appreciable quan-

tities of salt from entering. Laboratory investigation has shown that disintegration is not due to disruptive forces exerted by the salts in crystallizing, but rather to the chemical reaction between salts in solution and constituents of the cement. Disintegration is primarily due to chemical action, and any disruption which may occur under certain conditions as the result of crystallization is secondary.

The constituents of the cement attacked by the salts are lime, silica, and alumina. During the process of hardening of concrete, calcium hydrate is formed, and it is this material which is most readily attacked. The sulphates of sodium and magnesium in alkali waters react with the calcium hydrate to form calcium sulphate and sodium and magnesium hydrates. The part played in the process of disintegration by these newly formed compounds is not well understood and no doubt varies with the permeability of the concrete and quantity and movement of the alkali waters, but the final effect can not be disputed since the changes produced in the laboratory under controlled conditions have been verified by the inspection of good quality concrete which has been exposed to somewhat similar conditions in the field.

As a result of investigations in various chemical laboratories in which the solvent action of various salt solutions on cement and concrete has been measured, certain definite conclusions have been drawn. Studies made by Burke and Pinckney, at Montana State Agricultural College and reported in Bulletin No. 81, may be summarized as follows:

The disintegration of cement by alkali salts is principally due to reaction between these salts and the calcium hydroxide necessarily present in set cement. As a result of these reactions relatively insoluble *new compounds* are formed in the body of the cement structure. These new compounds have greater weight and require greater space than the $Ca(OH)_2$ replaced. New compounds force apart the particles of cement, thus weakening or breaking the binding material.

The results of a laboratory investigation at the University of Wyoming Experiment Station, reported by Steik in Bulletin No. 122, lead to the conclusion that "The ultimate cause of the disintegration of cement is by the alkalies forming compounds with the elements of the cement which subsequently are removed from the cement by solution."

The results of an extensive laboratory and field investigation of the action of the salts in sea water on cement, conducted by Bates, Phillips, and Wig of the Bureau, are reported in B. S. Tech. Paper, No. 12. Their work indicated that in the presence of sea water and similar sulphate-chloride solutions, "the most soluble element in the cement is lime. If the lime of the cement is carbonated, it is practically insoluble."

Thus it is seen that such investigations as have been carried on in the chemical laboratories have led to the agreement that certain constituents of the cement are attacked and dissolved by salts in solution. It has been found possible in the laboratory by artificial solutions to destroy almost completely test pieces of Portland cement mortars and concretes. It was also believed that laboratory conditions were probably more severe than exposure conditions which might ordinarily be encountered in the field. For the purpose of studying the behavior of mortars and concretes of known and good quality when exposed to the normal alkali soil conditions, the investigation described in detail in the foregoing pages was planned and started in 1913. The results, so far obtained, indicate that field conditions may be fully as severe and destructive to good quality concrete as were the early experiments carried out under laboratory conditions.

WASHINGTON, October 11, 1921.

DEPARTMENT OF COMMERCE

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OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 215

[Part of Vol. 16]

DURABILITY OF SOLE LEATHER FILLED WITH SULPHITE CELLULOSE EXTRACT

BY

ROY C. BOWKER, Associate Physicist

Bureau of Standards

JUNE 10, 1922

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DURABILITY OF SOLE LEATHER FILLED WITH SULPHITE CELLULOSE EXTRACT

By Roy C. Bowker

ABSTRACT

Four lots of leather were prepared and tested to determine the comparative durability of sole leather filled respectively with sulphite cellulose extract and with the ordinary tanning materials such as chestnut wood extract and quebracho extract. Physical data obtained as to the actual service tests and chemical analyses of both the new and worn soles failed to disclose a quality difference between the two leathers.

INTRODUCTION

The importance of utilizing the wood substance contained in the waste sulphite liquor, which at one time was discharged from the pulp mills as useless waste, is evidenced by the large amount of research which has been conducted on the subject in every wood-pulp-producing country.

One of the principal methods proposed for utilizing these waste liquors is the production of sulphite cellulose extract for use in making leather. This use of the material has been discussed with considerable interest, resulting in a remarkable diversity of opinion. It has been stated that the extract does not contain tanning properties, and hence is not a "true" tanning material as are such vegetable materials as oak bark, quebracho, and chestnut wood. It is generally considered that the material contains no tannin. However, experiments have shown that a hide treated with certain of the sulphite extracts will absorb as much as 25 per cent of substances which will preserve the hide, which is the essential function of a tanning material.

There are many different methods for treating the waste liquors to produce an extract for use in making leather, and hence there are correspondingly many different products. This may account in some measure for the varied results obtained from their use by investigators. Whether it is proposed to use the material either in tanning or filling, the waste liquor should be treated to remove such substances as iron and lime, which have a detrimental effect on the leather.

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American tanners have not been successful in their attempts to tan hides with sulphite cellulose extract, and it is generally considered as having no place in the tanyard.

It has found, however, a wide application as a filling material in the manufacture of sole leather. After the hides have been thoroughly tanned in the yard they still lack the firmness and weight required. It is the general commercial practice to produce these qualities by filling the leather with tanning materials by drumming, tempering, and dry dipping.

Since the opinion has often been expressed that sole leather filled with this extract was inferior, and since no known data on the subject were in existence, this investigation was made to determine the comparative durability of sole leather filled with sulphite cellulose extract and sole leather filled with the ordinary vegetable tanning materials.

DESCRIPTION OF LEATHER TESTED

Several tanners were approached regarding the preparation of leather for the tests, and three different establishments were chosen in order that the leather used might be representative. The history of the various lots of leather tested follows:

Lot No. 1.—This tannery made two brands of leather commercially, one of which contained sulphite cellulose extract. Five hides were selected for the test. The tannage up to the wringer was a vat tannage of 60 per cent chestnut oak and 40 per cent chestnut. The leather was then filled with chestnut extract by drumming and finished in sulphited quebracho extract. Five alternate bends were then bleached, oiled, dried, and rolled. The five remaining bends were bleached, partially oiled, dried, dry dipped in sulphite cellulose extract, redried, oiled, and rolled.

Lot No. 2.—Five hides were carried through the yard whole and then split after the third layer. Five bends were then extracted in drums with the ordinary tanning materials, tempered, bleached, oiled, and rolled. The remaining five bends were drummed in 100 per cent sulphite cellulose extract, lightly bleached, oiled, dried, dry dipped in warm sulphite cellulose extract of 5° Twaddle, oiled, dried, and rolled.

Lot No. 3.—In this tannery the hides were given 5 layers in the yard of 15 days each. No sulphite cellulose extract was used ordinarily in this tannery, but the company was interested in the proposed tests and prepared samples as desired. Four hides were

carried through the yard and were removed after the fourth layer. Four bends were then extracted in drums with 100 per cent sulphite cellulose extract, then tempered 5 days in a 50 barkometer tempering liquor of the same extract, oiled, dried, dry dipped in 70 barkometer liquor made from sulphite cellulose extract, and finished as usual. The remaining four bends were extracted in drums with a mixture of chestnut wood extract and quebracho extract (50 per cent each), then tempered 5 days in a 50 barkometer tempering liquor made up of 50 per cent each of chestnut wood and quebracho extract, oiled, dried, dry dipped in 70 barkometer chestnut wood liquor, and finished as usual.

LOT NO. 4.—This leather came from the same tannery as did lot No. 3. Four hides were used and the bends were removed after the fifth and last layer instead of after the fourth layer, as in lot No. 3. The two groups of bends received the same treatment given those in lot No. 3, with the exception of dry dipping, which was omitted.

WEAR TESTS

After the leather was received at the laboratory full soles were cut and matched for test in a manner similar to that described in Technologic Paper No. 138, so that the soles of each pair were cut from similar locations on the same hide. One sole of each pair contained sulphite cellulose extract and one contained the ordinary vegetable tanning materials used in the tannery which furnished the leather.

The leather was subjected to actual wearing test on laborers, laboratory workers, and office workers. The conditions of service were not uniform for all the different pairs of soles, some of which were worn on concrete floors, in machine shops, in boiler rooms, or in outside weather conditions.

TABLE 1.—Results of Wear Tests

Lot No.	Pairs of soles tested	Average iron per sole		Days wear per sole		Days wear per iron	
		O[a]	S[b]	O	S	O	S
1	73	9.91	9.66	118.7	115.7	11.97	11.98
2	90	9.60	9.54	94.4	90.5	9.84	9.49
3	54	8.69	8.51	59.6	58.1	6.86	6.83
4	63	8.44	8.48	63.7	67.9	7.55	8.01
Average		9.16	9.05	84.1	83.1	9.06	9.08

[a] O= Soles filled with ordinary vegetable tanning materials
[b] S= Soles filled either entirely or partially with sulphite cellulose extract

CHEMICAL ANALYSES

The following tables give the complete analyses for the different leathers both for the new and worn soles:

TABLE 2.—Analyses of New and Worn Soles, Based on 12 Per Cent Moisture Content

NEW SOLES

Material	Lot No. 1		Lot No. 2		Lot No. 3		Lot No. 4	
	O[a]	S[b]	O	S	O	S	O	S
Water soluble	25.19	31.69	26.81	28.96	31.53	29.01	24.30	25.25
Hide substance	30.53	28.02	33.62	34.11	31.01	34.00	37.42	35.60
Greases	3.09	3.06	4.49	4.38	4.51	4.61	3.38	4.12
Insoluble ash	.21	.29	.17	.25	.23	.29	.19	.29
Combined tannin	28.98	24.94	22.91	20.30	20.72	20.09	22.71	22.74
Degree of tannage	93	87	66	58	64	57	58	62
Glucose	3.17	7.86	5.87	6.78	11.02	11.32	4.45	2.48
Total ash	1.54	1.85	2.04	2.22	1.76	1.77	1.26	1.47
Free mineral acid	.23	.05	.53	.95	.53	.48	.14	.10
Soluble tans	15.06	19.37	16.34	13.24	13.07	11.63	11.68	15.95
Soluble nontans	10.12	12.27	10.47	15.75	18.49	17.40	12.62	9.30
Epsom salts	2.35	3.38	1.52	1.96	2.66	2.50	1.93	2.36
Worn Soles								
Water soluble	17.81	19.87	18.73	18.67	20.40	19.57	18.44	17.16
Hide substance	35.62	31.70	34.37	34.75	34.75	36.30	35.40	35.55
Greases	3.52	3.90	6.04	5.44	5.94	5.51	6.31	5.35
Insoluble ash	2.46	4.43	4.66	5.24	3.88	5.04	6.49	5.78
Combined tannin	28.59	28.10	24.20	23.90	23.03	21.58	21.36	24.16
Degree of tannage	80	89	71	69	66	60	60	68
Glucose	1.00	2.42	2.52	2.21	2.90	2.68	2.21	1.93
Total ash	3.97	5.70	5.82	7.59	5.10	6.86	7.80	7.56
Free mineral acid	.30	.15	.59	.73	.58	.44	.25	.25
Soluble tans	9.61	10.83	8.10	8.24	10.30	9.20	9.06	9.81
Soluble nontans	8.20	9.04	10.63	10.43	10.10	10.37	9.38	7.35
Epsom salts	2.44	2.63	2.25	1.35	2.57	2.15	1.78	2.13

[a] O= Leather filled with ordinary vegetable tanning materials
[b] S= Leather filled entirely or partially with sulphite cellulose extract

The results of the chemical analyses, broadly interpreted, indicate that from the analytical standpoint the quality of the leather was not impaired by filling with sulphite cellulose extract. A greater increase in the degree of tannage after wear for the sulphite-filled leathers than for the leathers filled in the usual manner is shown for each lot. The analyses also indicate that the sulphite cellulose extract is as well fixed in the leather as are the vegetable tanning materials such as chestnut and quebracho, and certainly more fixed than glucose, which was practically all withdrawn from the leather during wear, corrobrating previous data on this subject.

Under ordinary service conditions it would also be expected that most of the Epsom salts would be withdrawn from the leather during wear. In this particular series of tests many of the indi-

viduals wearing test soles worked with such materials as lime, cement, and magnesite. It is therefore not surprising that the analyses of the worn soles show no appreciable loss in Epsom salts.

In lot No. 1, the glucose content of the leather filled with sulphite cellulose extract is considerably more than the glucose present in the leather filled with the ordinary vegetable materials. This can be explained by the fact that the tanner of these leathers uses a greater amount of glucose in filling the former leather than is the custom in filling his regular tannage.

The large difference in glucose content between lots 3 and 4, which were made by the same tanner, is caused by the fact that lot No. 3 was removed after the fourth layer instead of after the fifth layer, as for lot No. 4. Lot No. 3 was then in a slack tanned condition and would more readily absorb a greater amount of glucose than leather more thoroughly tanned, as was lot No. 4.

TABLE 3.—Analyses of Sulphite Cellulose Extracts Used

Material	Used in lot No. 1	Used in lot No. 2	Used in lots No. 3 and 4
Materials absorbed by hide powder	30.09	26.56	27.25
Nontannins	24.71	25.12	24.30
Insolubles	.07	.00	.12
Moisture	45.13	48.33	48.33
Total solids	54.87	51.68	51.67
Soluble solids	54.80	51.68	51.55

Analysis of lot No. 1 was made from sample furnished by the tannery. The remaining analyses were furnished by the tanners who furnished the leather to which reference is made by the lot numbers. The tanners of lot Nos. 1, 3, and 4 referred to the sulphite cellulose extract used, as "spruce extract." The tanners of lot No. 2 referred to the sulphite cellulose extract used as that manufactured by the Robeson Process Co., New York City.

The tanners who furnished the leathers were C. C. Smoot & Sons, The American Oak Leather Co., and the Ashland Leather Co.

SUMMARY

As a result of these tests the following observations can be made regarding the sulphite cellulose extracts used in this investigation as fillers for sole leather:

1. Leather filled either partially or entirely with sulphite cellulose extract is as durable as leather filled with the ordinary tanning materials, such as chestnut and quebracho.

2. As reflected by the chemical analyses, this extract is equally as firmly fixed in the leather as these vegetable tanning materials.

3. The use of such a material instead of chestnut and quebracho would conserve these materials for use in the actual tanning processes for which they are suitable and for which sulphite cellulose extract has not been successfully used.

4. It is probable that this material could be used as a filler in place of the more soluble glucose, thereby producing a more waterproof leather.

5. Leather filled with this material can be made which will have as light and uniform a color as leather filled with the ordinary materials. This was the case for lots No. 1 and 2. There was a slight difference in the color in lots No. 3 and 4, the leather filled with sulphite cellulose extract being a little darker.

6. Using this material as a filler has no more effect on the aging of the leather than the ordinary materials, since samples of these leathers which have been in the laboratory for over two years are still in a satisfactory and pliable condition.

WASHINGTON, April 8, 1922.

DEPARTMENT OF COMMERCE

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S. W. STRATTON, DIRECTOR

No. 216

(Part of Vol. 16)

PROPERTIES OF ELECTRICAL INSULATING MATERIALS OF THE LAMINATED PHENOL-METHYLENE TYPE

BY

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J. L. PRESTON, Physicist

Bureau of Standards

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PROPERTIES OF ELECTRICAL INSULATING MATERIALS OF THE LAMINATED PHENOL-METHYLENE TYPE

By J. H. Dellinger and J. L. Preston

ABSTRACT

The manufacture of phenolic synthetic resins as applied to the fabrication of electrical insulating material has only become commercially important within the last 20 years. Some of the older materials were not suited for particular purposes or were too expensive, and the phenolic type was developed to meet a real commercial need. The materials of this type may be broadly classified as laminated materials or molded materials.

This paper is concerned exclusively with materials of the laminated, phenol-methylene type, which are made by building up sheets of paper, fiber, or fabric which had been previously impregnated or coated with phenolic (synthetic) varnish to some desired thickness and then subjecting the stack to comparatively great pressure in a heated hydraulic press. This laminated type has been the subject of a comprehensive investigation at this Bureau. The varnishes used in the manufacture of the laminated materials whose properties have been investigated are Bakelite, Condensite, and Redmanol, manufactured, respectively, by the General Bakelite Co., Condensite Co. of America, and the Redmanol Chemical Products Co.

The companies who fabricate these laminated materials from the phenolic binder (varnish) and filler (paper, fiber, or fabric), with the grades on which data are given in this paper, are: Diamond State Fibre Co.—Condensite Celoron: Grade 10, fiber base; grade 15, fiber base; grade 20, fabric base. The Continental Fibre Co.—Bakelite Dilecto: Grade XX, paper base; grade X, paper base; grade CB, fabric base. The Formica Insulation Co.—Formica: Grade M, paper base; grade M–2, paper base; grade P, paper base; grade R, fabric base. Westinghouse Electric & Manufacturing Co.—Bakelite Micarta: Grade 32–X, paper base; grade 21–X, paper base; grade 323, paper base; grade 213, paper base; grade 21–D, fabric base.

The various properties or effects which have been determined for this type of material are listed below. Experimental data or other information are given relative to each of these properties. These tests cover radio-frequency phase difference or power loss, dielectric constant, and flash-over voltage, direct-current surface resistivity and volume resistivity, tensile strength, modulus of elasticity (tensile), proportional limit, modulus of rupture, modulus of elasticity (transverse), Brinell hardness, scleroscope hardness, impact strength, permanent distortion, density, moisture absorption, machining qualities, thermal expansivity, and the effects of heat, acid, and alkali.

The data on these properties have been arranged in such a manner as to be conveniently available for reference, either by a person desiring detailed information or by a person interested only in a general way in the more important properties. The methods of performing the various tests are also very fully described in a Bureau publication referred to in the text.

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I. INTRODUCTION

1. HISTORY OF SAMPLES

All of the data which the authors of this paper present were obtained on samples of laminated, phenolic insulating materials received by the Bureau between December 20, 1917, and August 24, 1919. Some observations made on a limited number of later samples have indicated that the various phenolic insulating materials have been more or less improved in their electrical and mechanical properties.

2. THE DEMAND FOR THE PHENOLIC INSULATING MATERIALS

Phenolic insulating materials have been introduced during the past few years for a wide variety of uses. In electrical work they are used for the same purposes for which hard rubber (sometimes called ebonite or vulcanite) has been used, namely, for the insulating parts of electrical instruments and apparatus. The ever-increasing demand for raw rubber in other industries, however, renders it too expensive for general use as an insulating material. The cost of the raw material has increased the tendency to load hard rubber with fillers or to use reclaimed rubber. While hard rubber has a number of the properties desirable in an electrical insulating material, such as high electrical resistivity, very small power loss, and ease of machining, it has, on the other hand, certain undesirable qualities, such as low tensile strength, brittleness, high thermal expansivity, deterioration in sunlight, and because of a tendency to soften at moderate temperatures it shrinks and warps.

Composition materials using shellac, pitch, or similar compounds as a binding medium are used, but for most radio uses the more expensive materials using phenol condensation products as the binder have proved more satisfactory. The phenolic materials are described later in section II.

3. NEED FOR THIS RESEARCH

When the United States entered the war against Germany, the various Government departments and private manufacturers were making demands on a few manufacturers of laminated materials of the phenol-methylene type beyond the capacity of their manufacturing equipment. It was the practice in ordering insulating material for radio and other electrical apparatus to specify, more or less arbitrarily, the use of insulating material of a certain trade

name instead of specifying the qualities or properties required for the particular use in view. This condition led the War and Navy Departments and some of the manufacturers of phenolic insulating materials to seek data on the various properties of the materials. Some of the manufacturers began to inquire into the faults of their material with a view to correcting their processes, if possible, or choosing their basic naterials so that their product would receive Government approval.

In October, 1917, the Formica Insulation Co. requested the Bureau of Standards to make measurements on the properties of Formica. Other companies whose products were included in the measurements that followed are given on page 501. The manufacturers had little idea concerning the nature of the tests necessary, but were willing to supply samples, information, and suggestions. Phenolic insulating material was being used by the Government in very large quantities for radio apparatus, and so the immediate aim was to obtain such data as would determine the suitability of the material for radio uses. The work soon broadened into a general research on the properties of these materials.

Prior to the time the Bureau of Standards started the tests on Formica there had been practically no measurements made of the properties of insulating materials at radio frequencies. This meant that the composition of the insulating materials using phenol varnish had to be studied, tests had to be devised, and apparatus designed and constructed for the measurement of various properties.

While much valuable information had been previously collected on these and other types of insulating material by manufacturers and testing laboratories, their work was confined largely to mechanical properties, 60-cycle puncture voltage, volume and surface resistivity, and dielectric constant. The data thus available from various sources are not related—that is, the electrical and mechanical data were seldom obtained from tests on the same sample. A reliable comparison of the several materials can not be made unless the properties are all measured on the same sample because of the very considerable variations from sample to sample. The work described herein has, consequently, been done with samples of such size that specimens for all tests on a particular grade of material could be cut from the same sheet.

The results of this work may therefore be of value to the manufacturers of these materials, to various departments of the Govern-

ment who buy such material in large quantities, and to manufacturers and users of electrical apparatus. It is shown that the properties of various samples of the same grade of material vary. A study of the several properties as found for the different makes and grades of material should lead to improved products as experience in the methods of manufacture increases and the needs of the consumer are better understood.

From the experience gained in this investigation it seems evident that there is no one insulating material of this type that could be cited to answer the broad question, "Which is the best insulating material?" The peculiar demands put upon the material when used in a particular place must be studied and a material chosen that has the best combination of properties to meet the need. As a rule, it may be stated that to obtain the best electrical properties the mechanical properties must be sacrificed to a certain extent. Other general conclusions are presented in section V, "Discussion of Results."

4. SCOPE OF THE WORK

To obtain comparative data on the various kinds and grades of laminated phenolic insulating materials, the following electrical, mechanical, and other properties have been measured for each grade and for several thicknesses of each grade where possible: Volume resistivity and surface resistivity, voltage effects at radio frequencies, phase difference or power factor and dielectric constant at radio frequencies, ultimate tensile strength, proportional limit and modulus of elasticity (tensile), modulus of rupture (transverse), proportional limit and modulus of elasticity (transverse), Brinell hardness, scleroscope hardness, impact strength, permanent distortion under dead weight, density, moisture absorption, machining qualities, thermal expansivity, heat effects, and effects of acid and alkali. The various tests made in this research are not necessarily the final word on the important properties requiring consideration. In fact, there are other tests that are now being considered for continued work on this same type of material. See section III–1 for the reasons why these properties were selected.

For every material the various properties were measured upon test specimens cut from the same sheet of insulating material. For reasons already stated principal emphasis was placed on measurements of radio properties.

Dielectric strength or puncture voltage at low frequencies has not been studied for two reasons: First, the significance of such measurements is somewhat doubtful and in particular is nil at radio frequencies, and, second, because the various manufacturers and some users of the materials have had many puncture voltage tests made at private testing laboratories. Other tests which were intentionally omitted are crushing strength and shear strength across and with the laminations. For the sake of comparison with the phenolic materials, in section V–23 is given a comprehensive comparison of laminated and molded phenolic materials, hard rubber, and vulcanized fiber. This paper deals primarily with the laminated and not the molded phenolic materials.

Kind of Samples and Scheme of Numbering.—The test samples for measurement of the various properties were, in general, cut from standard-sized sheets of insulating material such as are furnished by the manufacturers to the trade. (They were slabs or sheets approximately 61 by 93 cm (24 by 36 inches) or 97 by 97 cm (38 by 38 inches) and in varying thicknesses, usually between 6 and 13 mm (¼ to ½ inch). Specimens for the measurements on all properties were cut from the same large sheet, so the results on the various properties are comparable.

Each sheet was assigned an arbitrary number when received, this number being the "B. S. Sample No." given in the tables of section IV. A record was made of this number, maker of sample, grade, color, thickness, size, nature of varnish and filler (base), and date of receipt.

When preparing test specimens cut from these large sheets, each of the several specimens cut for a particular test were assigned arbitrary numbers having no relation to the "B. S. Sample No." of the sheet. As an example, three tensile strength specimens might be cut from sample sheet No. 51 and be stamped A, 3C, and X. When these samples were mixed with many others of the same thickness, color, and finish, it would be difficult for the person doing the testing to check his own results from a knowledge of other results on similar materials.

Information not Included in Present Publication.—The description of the method of making the various tests is given in a separate publication entitled "Methods of Measurement of Properties of Electrical Insulating Materials." The bibliographies of periodicals and patents, etc., are also prepared separately as laboratory reports under the titles, "List of Books and Periodicals

on Tests, Properties, and Uses of Laminated Phenolic and Other Electrical Insulating Materials," and "List of the More Important United States Patents Covering Electrical Insulating Materials and Methods of Manufacture." A limited number of copies of these two reports are available at the radio laboratory of this Bureau.

5. COOPERATION IN THIS RESEARCH

The Bureau of Standards has had the hearty cooperation of the manufacturers at all stages of this work. The four manufacturers of laminated phenolic insulating materials mentioned above sent large numbers of samples of their products at the Bureau's request. The samples sent by these companies had a considerable money value. The companies not only sent samples willingly but contributed advice, experience, and discussion at various phases of the work. The following men representing these companies were particularly helpful to the Bureau in giving such assistance and cooperation: John A. Holmes and James McIntosh of the Diamond State Fibre Co.; W. C. Anderson and C. L. Bonham of the Continental Fibre Co.; D. J. O'Conor and W. W. Ryerson, eastern representative, of the Formica Insulation Co.; J. G. Miles and C. E. Skinner of the Westinghouse Electric & Manufacturing Co.

Besides the manufacturers of the laminated materials a number of the companies manufacturing the phenolic varnishes and molded phenolic materials took an interest in this work and assisted in its progress. The three companies which manufacture the phenolic varnishes were the Condensite Co. of America, the General Bakelite Co., and the Redmanol Chemical Products Co. The first two named also submitted samples of molded materials. The results of tests on molded insulating materials, built-up mica, and other materials are not included herein.

The measurements of the various properties described herein were made by the respective sections of the Bureau which specialize in those measurements. For the reasons stated, the general research was originally undertaken by the radio laboratory, and it was at the initiative of the radio laboratory that the several measurements were made. Besides measuring the radio-frequency properties the radio laboratory cut and prepared the test specimens for all measurements.

The work began in the latter half of 1917. Work on the methods of measurement was done by G. C. Southworth of the radio

laboratory, who also made many of the radio-frequency measurements and arranged for other tests. Credit for the results accomplished is due him. Measurements of phase difference were made by Miss H. H. Smith and E. L. Hall. The collecting and tabulating of the data and opinions on hard rubber, vulcanized fiber, and molded and laminated phenolic materials were done by E. L. Hall. Prof. H. W. Harmon and E. S. Purington were instrumental in developing the high-voltage radio-frequency testing set designed by G. C. Southworth. R. S. Ould prepared a bibliography of periodicals, etc., and an extensive patent list. Other members of the radio laboratory who have assisted directly in this work are F. E. Baldwin, H. B. Daniel, and N. Montgomery.

The following members of the Bureau of Standards staff cooperated by making the tests in which they had particularly specialized: Volume and surface resistivity, H. L. Curtis, C. N. Hickman, and C. M. Sparks; moisture absorption and density, E. L. Peffer; thermal expansivity, W. H. Souder and Peter Hidnert; effects of elevated temperature, E. F. Mueller and L. I. Dana; mechanical properties, H. L. Whittemore, H. A. Anderson, and G. M. Deming.

II. DESCRIPTION OF LAMINATED PHENOLIC INSULATING MATERIALS

1. DESCRIPTION OF THE COMMERCIAL GRADES

Data on the various grades of laminated, phenolic materials regularly manufactured by the various companies are given below. Further information on the particular grades can be found in the descriptive and advertising booklets furnished by the companies. Besides these standard grades the manufacturers sometimes make special grades to suit the particular requirements of a purchaser.

TABLE 1.—Description of Grades of Condensite Celoron Manufactured by Diamond State Fibre Co., Bridgeport, Pa.

Grade	Color	Finish	Base (filler)	Binder
15	Black	Polished or dull	Vulcanized fiber	Condensite phenol varnish
10	Natural	do	do	Do.
25	Black	do	Canvas	Do.
20	Natural	do	do	Do.
35	Black	do	Asbestos	Do.
30	Natural	do	do	Do.

TABLE 2.—Description of Grades of Bakelite-Dilecto and Continental-Bakelite Manufactured by the Continental Fibre Co., Newark, Del.

BAKELITE-DILECTO

Grade[a]	Color	Finish	Base (filler)	Binder
XX	Black or natural	Polished or dull	Paper	Bakelite phenol varnish
XXX	do	do	do	Do.
X	Natural	do	do	Do.
X (extra hard)	do	do	do	Do.
G	Black or natural	do	do	Do.
A	do	do	Asbestos	Do.
S	Black	do	Paper and hard rubber	Do.

CONTINENTAL-BAKELITE

CB	Black or natural	Polished or dull	Canvas	Bakelite phenol varnish
CBL	do	do	Light canvas	Do.

[a] The X grade can also be furnished with the outer surfaces black.

TABLE 3.—Description of Grades of Formica Manufactured by the Formica Insulation Co., 4614 Spring Grove Avenue, Cincinnati, Ohio

Grade	Color	Finish	Base (filler)	Binder
M	Black or natural	Polished or dull	Paper	Redmanol phenol varnish
M-2	do	do	do	Redmanol cresol varnish
P	Natural	Dull	do	Redmanol phenol varnish
R	do	do	Canvas	Do.

TABLE 4.—Description of grades of Bakelite Micarta Manufactured by Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.

Grade	Color	Finish	Base (filler)	Binder
32-X	Black	Polished or dull	Paper	Bakelite phenol varnish
21-X	Natural	do	do	Do.
323	Black	do	do	Do.
213	Natural	do	do	Do.
21-D	do	do	Canvas	Do.

2. DESCRIPTION OF MATERIAL AND METHOD OF MANUFACTURE

It is not within the scope of this paper to give a detailed description of the process of manufacture of this type of material. However, a general description may be of value to those not acquainted with the process. For those desiring a more complete understanding of the various processes the list of patent numbers and titles mentioned on page 506 will furnish a source of detailed information. The pamphlets listed in the bibliography mentioned on the same page will furnish some information also.

The two essential parts of this material are the base or filler and the binder. The base consists of sheets of paper, fabric, or fiber, and the binder is a phenol (carbolic acid) condensation product.

Bakelite-Dilecto, Continental-Bakelite, and Bakelite Micarta have as a binder a phenol varnish (condensation product) manufactured by the General Bakelite Co., Perth Amboy, N. J. The makers of Condensite Celoron use a phenol varnish manufactured by the Condensite Co. of America, Bloomfield, N. J., and the makers of Formica a phenol varnish manufactured by the Redmanol Chemical Products Co., 636 West Twenty-second Street, Chicago, Ill. The same type of phenol varnishes are used by many companies in making what are called molded materials, in which the base or filler consists usually of a powdered material instead of sheets, as in the laminated materials.

VARNISH.—The varnish referred to in this report as varnish or phenol condensation product used in the above insulating materials as a binder is, as the term designates, a varnish composed chiefly of phenol. In general, the varnish is the result of the chemical reaction of any suitable hydroxyl aromatic compound, such as phenol or its homologues and hexamethylenetetramine or a suitable equivalent active methylene body. The reaction, carried on in the presence of heat, may be stopped at any convenient point, so that the resulting resin may have any characteristic between a fusible, soluble resin and an almost infusible, insoluble resin. For use in this type of insulating material the reaction must be stopped while the resin is both fusible and soluble. The resin in this condition is then dissolved in a suitable solvent, such as alcohol or acetone, and is then ready for use as the varnish binder in the laminated insulating materials.

The foregoing description of the process of manufacture of phenol varnish is not meant to be an analysis for any one kind of phenol varnish. It is a general process. Further details may be found by reading the patents covering this class of materials (see p. 506). Neither does this description give a true idea of the complexity of the processes nor the probability of a nonuniform product.

LAMINATING.—Paper, fabric, or fiber may be more or less easily impregnated or coated with a phenol varnish. If sheets of paper have been so treated and dried at a low temperature, they are ready, then, to be built into a sheet of insulating material of any practical thickness. After a certain number of the impregnated sheets have been stacked together the stack is put in a hydraulic press and subjected to pressure and heat. This heating tends to complete the chemical reaction in the varnish, which was stopped

in the making of the resin to permit dissolving. The press heating tends to "turn-over" or convert the varnish to an insoluble, infusible state. The stack of impregnated sheets has now become a mechanically strong, dense sheet of insulating material.

Grain.—Since paper has a grain—that is, a unidirectional fibrous structure and a resulting greater strength with the grain—it is evident that if each sheet of paper is built into the stack in the same direction with reference to the grain, one should expect the resulting compressed insulating material to have a grain. This point will be raised again in the analysis of data on mechanical properties in section V, "Discussion of results."

Finish.—The condition of the surface of the finished sheet of insulating material is dependent on the condition of the face plates of the hydraulic press, which are called platens. If these are polished, the sheet will have a polished surface; whereas if the platen faces were unpolished, the sheet will have a dull surface. A dull surface may be polished by buffing with oil and rouge, but such a method may affect the electrical properties of the surface of the insulating material.

Color.—At some stage in the manufacture or use of the phenol varnish a dye may be added, usually black. It is quite easy to recognize the various grades of laminated materials if natural colored samples only are considered, but to know each material and grade when all samples are black requires a thorough understanding of many details. The average user of the material would have much difficulty in checking his stock if the materials or grades were mixed by him or the jobber. Furthermore, some of the retailers of these laminated phenol-methylene insulating materials fail to appreciate or know any difference in grades of a particular kind of material, so the consumer may misjudge the material by not receiving the grade best suited to his needs. The manufacturers could assist by stamping the grade designation on each sheet, but the user must always take precautions to inform himself as to what grade of material he really has.

III. PROPERTIES MEASURED

1. REASONS FOR CHOICE OF PROPERTIES

(A) CHOICE OF ELECTRICAL PROPERTIES

Phase Difference or Power Factor.—The principal aim of the research being to determine the suitability of the materials for electrical uses, most attention was given to the electrical

properties. The limitations of an insulating material used in alternating-current apparatus are measured by the magnitude of the power loss caused by dielectric absorption. This is a phenomenon which causes the material to heat when a varying current flows in it. The amount of this property is given by a quantity called the phase difference, which is explained just below in section III–2. This property is measured at radio frequencies, (*a*) because it is more accurately measurable at radio frequencies than at low frequencies, (*b*) because this research has particularly in view the radio uses of insulating materials, (*c*) because the value of phase difference at radio frequencies largely determines the radio-frequency voltages the material will stand without injury, and (*d*) power loss in insulating parts introduces resistance into the circuit of radio apparatus and diminishes selectivity. A knowledge of phase difference or power factor sheds light on the basic theory of action of electrical insulating media.

Dielectric Constant.—The dielectric constant is an important property in an insulating material to be used in making up a condenser. It determines the amount of alternating current which flows when an alternating voltage is impressed on the condenser. It thus plays an important part in determining how much the condenser heats and the high-frequency voltage at which the insulating material is injured. This property is easily measured simultaneously with the measurement of phase difference. Both these properties are measured at radio frequencies. The dielectric constant is not greatly different at low frequencies and at radio frequencies.

Voltage Effects at Radio Frequencies.—No measurements of the dielectric strength or puncture voltage at commercial frequencies were made, since, as already stated, the materials are seldom used where voltages are so high as to be destructive. Measurements of the effects of high voltage at radio frequencies have been included, however, because these materials are used as panels supporting the parts of generators of radio-frequency current in which fairly high voltages are present. The voltages required for destruction of the material at high frequencies used in radio are very much smaller than for low frequencies. The effects of voltage are discussed further in section V, "Discussion of results."

Insulation Resistance.—Generally speaking, the phenolic materials are used for insulating purposes at voltages which are

not so high as to threaten destruction of the material. For low-voltage work it is important to know how well the materials insulate. Hence, measurements were made to determine insulation resistance. Electricity leaks along the surface of an insulator as well as through its volume, and so it is necessary to determine both the surface resistivity and volume resistivity. These and the other properties are carefully defined later in section III.

(B) CHOICE OF MECHANICAL PROPERTIES

A material for any purpose must satisfy certain mechanical requirements or the most splendid electrical properties will be of no avail. For instance, it must be able to bear the weight it has to carry without breaking. Certain grades of the material are sold, primarily, for mechanical purposes. Such grades are usually very good for insulating purposes also, where only low-frequency currents are considered and the chief requirements are mechanical. Whether the chief requirements are electrical or mechanical, the mechanical properties must be known. Such data are necessary in the designing of electrical apparatus and for comparative information on the various kinds and grades of insulating material.

Density and Moisture Absorption.—The absorption of moisture has an important effect on many of the properties. The reasons for measuring density and moisture absorption are analyzed elsewhere in this paper (sec. III–1). The percentage of moisture absorbed by a sample when immersed in water for a stated time is a measure of how thoroughly the phenol varnish has protected the cellulose fiber against moisture. Composite material, such as the laminated phenol-methylene type of insulation, is capable, therefore, of absorbing varying amounts of moisture from the atmosphere. Hard rubber also absorbs moisture but to a much smaller extent. The effect of this naturally absorbed moisture is shown by the data on the effect of season on phase difference (pp. 609 to 610) and on surface resistivity (p. 610) in section V, "Discussion of results."

Tensile Strength.—Tensile strength data furnish specific and comparative information to those designing electrical insulator parts which are under mechanical stress. The modulus of elasticity (tensile) shows a peculiarity of this type of material. Its modulus is very small in comparison with metals. The various makes of insulating materials differ somewhat in this respect, but

the greatest difference is between grades of the same kind of material. This difference is probably owing to the different percentages of varnish in the different grades. The proportional limit of the materials gives information as to the stress which can not be exceeded without gradual yielding taking place in the material.

TRANSVERSE STRENGTH.—Transverse or cross-bend strength data are equally important. The greater portion of the materials discussed in this report are of a laminated structure. When such laminated materials are subjected to a bending stress, there is a tendency for the laminations to shear owing to the different strain on the extreme (outer) layers. Tensile and transverse strength data give comparative knowledge of the strength of the different laminated materials and also furnish material for comparison with like data on hard rubber and other materials. In transverse strength tests modulus of rupture and modulus of elasticity have been considered. Modulus of elasticity values are missing for some materials listed in the tabulated data shown on pages 524 to 533. Some samples were tested without using a deflectometer, so there were not sufficient data to compute modulus of elasticity. A few measurements of proportional limit (transverse) were made. Some of these data are given on page 574 in connection with data on proportional limit (tensile).

HARDNESS.—Hardness of the various insulating materials has been measured for several reasons. The laminated phenolic materials are being substituted for hard rubber, the hardness of which varies considerably with temperature. Therefore, it has seemed fitting to measure the relative hardness of the various materials at different temperatures. Also, the hardness of the phenolic materials varies with the length of time the sheets have been cured. Hardness data are being accumulated with the hope that it will throw some light on other mechanical and electrical data.

IMPACT STRENGTH.—Impact tests determine the brittleness of a material or its ability to withstand a suddenly applied force. Such tests show differences in the various kinds of material, but chiefly in grades. Percentage of varnish, kind of filler, and length of curing influence the impact strength values.

PERMANENT DISTORTION.—Under the heading of distortion tests come measurements of permanent distortion (or warp under stress) and natural warp. The measurements of permanent dis-

tortion or warp under stress were made to compare one phenolic material with another and all such with hard rubber, since one of the chief difficulties with hard rubber is that it warps under stress. The warping of hard rubber increases when either stress is increased or heat is applied, but this paper will contain no data of comparative warp under stress and heat.

Machining Qualities.—Since this investigation was started to show how one laminated phenolic insulating material compared with another and how all such materials compared with hard rubber, practical considerations make it necessary to compare machining qualities. Hard rubber can be sawed, drilled, tapped, turned, threaded, and milled with comparative ease. Of course, hard rubber is brittle, but this can be provided against in the designing and machining of parts. The laminated insulating materials of the phenol-methylene type are comparatively tough, hard to machine, and dull the machine tools rapidly. The different kinds and grades of such material may differ in this respect. The extensive arbitrary test scheme outlined in a separate Bureau publication mentioned on page 506 was intended to approximate general simple machining operations, such as might be performed in the average shop using the various phenolic insulating materials, and to obtain statements from the Bureau of Standards machinists concerning their preferences of the various kinds and grades of insulating material for different operations, based on their own work.

(c) Choice of Thermal and Chemical Properties

Thermal Expansivity.—The use of insulating materials of the phenol-methylene type on delicate instruments of varied types has made it necessary to know the thermal expansivity of the various kinds of material. If the delicate instruments whose construction includes such material are to be used where there are appreciable temperature changes, it is important to know whether any set of changes with temperature will be the same during a similar subsequent temperature cycle.

Heat Effects.—An attempt was made to analyze the effect of relatively high temperatures on the various laminated insulating materials. This test was used to determine, if possible, which materials were best adapted to the higher temperatures.

Chemical Effects.—Because of the multitude of uses to which the phenolic insulating materials are put it seemed necessary to determine some effects of acid and alkali on them. We have had numerous requests for such information. It is probable that such

tests are more important on the molded types of phenol-methylene materials because of the tendency to replace the more or less brittle hard-rubber containers for acids with the molded phenolic materials.

2. DEFINITIONS OF ELECTRICAL PROPERTIES

PHASE DIFFERENCE.—The property called phase difference is a quantity which gives a measure of the power loss accompanying production of heat in the material when an alternating current flows. In most materials this power loss or heating is caused by the phenomenon of dielectric absorption. This phenomenon is somewhat like viscosity in a liquid and is sometimes called "dielectric viscosity." The power loss can be caused by a very low volume resistivity, but materials of such very low resistivity are hardly suitable for use as insulators.

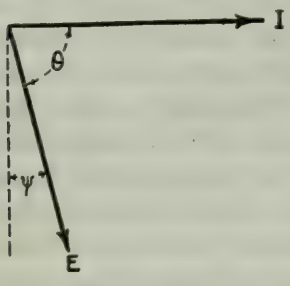

FIG. 1.—*Diagram of phase relation of I and E*

The phase difference (ψ) is magnified.

The phase difference has a very simple relation to a more widely used quantity, the power factor. It is, in fact, equal to it in most cases. When alternating current flows in a condenser having a solid insulating material between the plates, the current is not exactly 90 degrees out of phase with the impressed voltage, because of the existence of the heating or power loss. Instead of being exactly 90 degrees, the phase angle is some slightly smaller value and the cosine of this phase angle is called the power factor. The small difference between the phase angle and 90 degrees is called the phase difference. The power loss in the material is

$$P = EI \cos \theta,$$

where E is the voltage across the condenser, I the current, and θ the phase angle (see Fig. 1). The factor $\cos \theta$ is the power factor.

Letting ψ = the phase difference or 90 degrees $- \theta$,

$$P = EI \sin \psi.$$

It follows that

$$\sin \psi = \cos \theta.$$

That is, the sine of the phase difference is equal to the power factor. In all except extremely poor condensers ψ is small, $\sin \psi$ is practically equal to ψ, and since $\sin \psi$ is equal to the power factor it follows that usually ψ (in radians) is equal to the power

factor. Phase difference is usually expressed in degrees, and power factor in per cent. Power factor in per cent is obtained by multiplying phase difference in degrees by 1.75.

Since the phase difference in radians is usually equal to power factor, therefore

$$\psi = \frac{P}{EI}. \tag{1}$$

In words, phase difference is the ratio of power dissipated as heat (P) to total power flowing (EI).

$$\psi \text{ in degrees} = \frac{0.1079\ R \text{ ohms} \times C\mu\mu f}{\lambda \text{ meters}}. \tag{1a}$$

If one wishes to express this property of an insulating material in terms of watt loss (P),

$$\begin{aligned} P &= EI\,\psi \\ &= 2\,\pi\, f\,\psi\, CE^2 \\ &= \frac{\text{constant} \times f(\psi \text{K})\ SE^2}{T}, \end{aligned}$$

where E is the voltage across the condenser,
I is the current,
ψ is the phase difference in degrees,
f is the frequency in cycles per second,
K is the dielectric constant,
S is the area of one of the condenser plates in square centimeters,
T is the thickness of the dielectric in centimeters.

Also $P = RI^2$ where R is the equivalent resistance in ohms.

Dielectric Constant.—The dielectric constant of an insulating material is the property which characterizes the material in determining the capacity of a condenser employing it. It is the quantity K in

$$C = 0.0885\ \frac{K\,S}{T}, \tag{2}$$

where C is the capacity of a flat-plate condenser in micromicrofarads, S is the area of one of the condenser plates in square centimeters, and T is the thickness of the insulating sheet in centimeters. The dielectric constant of air is 1 and the dielectric constant of most substances is between 1 and 10, except water, which has a dielectric constant of 81.

Flash-over Voltage.—Flash-over voltage is here defined as the effective radio-frequency voltage necessary to arc over the surface of an insulating material between skirted brass studs (diameter = 2.0 cm) placed with a distance of two centimeters between their nearest points.

$$E = \frac{1.6(10)^{11} I}{f C} = \frac{530\lambda I}{C}, \tag{3}$$

where f is frequency of the alternating current, λ is wave length in meters, C is the capacity in micromicrofarads, E is volts, and I is amperes. The definition of flash-over voltage is not complete without further specification of time and other factors. (See paper mentioned on p. 506 and sec. V–3 of this paper.)

Electrical Resistivities.—The current which flows between two conductors insulated from each other by a solid material is made up of two parts—that which flows through the insulator proper and that which flows through a film of moisture or other semiconducting material on the surface of the insulator. The relative importance of these depends on the resistance of the two paths. Since water, even if very pure, conducts much better than the ordinary solid insulators, a very thin film of water may have much less resistance than the insulator.

Volume Resistivity.—The volume resistivity ρ of a material is defined as the resistance between two opposite faces of a centimeter cube. For any specimen of cross section S and length l the resistance is

$$R = \frac{\rho l}{S} \text{ or } \rho = \frac{RS}{l}. \tag{4}$$

Surface Resistivity.—By analogy the surface resistivity is defined as the resistance between two opposite edges of a square surface film. If the film is uniform over a surface,

$$\sigma = \frac{R'b}{l}, \tag{5}$$

where σ is the surface resistivity and R' the resistance of a rectangle of the film of length l and breadth b. If the thickness of the film is t, the volume resistivity of the film will be

$$\rho' = \frac{R' b t}{l} = \sigma t.$$

or, $\sigma = \rho'/t$.

Since σ, the surface resistivity, depends upon the thickness of the film, it is not a property solely of the material of the film, and the term "resistivity," which is generally used to express the property of a material, can not strictly be applied. However, since both the thickness t and the volume resistivity ρ' of the surface film depend, under any given conditions, upon the material on which it is deposited, surface resistivity may be considered as a property of the material on which the film is deposited. Thus, we speak of the surface resistivity of glass, hard rubber, etc., though these materials only serve for condensing the moisture and do not carry any of the current.

For a more complete explanation of volume and surface resistivity, see B. S. Sci. Papers, No. 234, by H. L. Curtis, entitled "Insulating Properties of Solid Dielectrics."

3. DEFINITIONS OF MECHANICAL PROPERTIES

Density.—The density of a substance is its mass per unit volume. In the cgs system density values are expressed numerically by the number of grams per milliliter. It is more customary among engineers to speak of density in terms of grams per cubic centimeter, so all the tables giving Bureau of Standards density data are headed "grams per cubic centimeter." This is slightly in error, but values expressed in g/ml and g/cc should vary by only 27 parts in 1 000 000.

Moisture Absorption.—Moisture absorption is here given the arbitrary definition: The percentage by weight of water absorbed by a sample (cut 5 by 10 cm by the natural thickness of the material) when immersed in water at room temperature for 24 hours. Results obtained on samples of any other size or shape are not comparable with moisture absorption as here defined.

Ultimate Strength.—Ultimate strength (tensile) of a material is the pulling force, in pounds, necessary to break a given sample, divided by the area of the cross section in square inches.

Modulus of Elasticity.—Modulus of elasticity (tensile) is the ratio of the magnitude of the stress to that of the accompanying unit elongation produced.

$$\text{Modulus of elasticity (tensile)} = \frac{P\,L}{b\,d\,l}, \qquad (6)$$

where P = load in pounds, L = distance in inches between gage marks, l = elongation in inches, b = width of sample in inches at reduced section, d = thickness of sample in inches.

Where cylindrical samples are used, modulus of elasticity (tensile) $= \frac{PL}{al}$ where a = area of reduced section in inches, bd is equivalent to a. The formula $\frac{PL}{al}$ may be written $\frac{\frac{P}{a}}{\frac{l}{L}}$,

$\frac{P}{a}$ being the stress per unit area or the measure of stress, and $\frac{l}{L}$ is the strain per unit length or the measure of strain. The formula $\frac{P\ L}{a\ l}$ or $\frac{P\ L}{bd\ l}$ is then a ratio of stress to the accompanying strain, this ratio being constant within the limits of elasticity.

PROPORTIONAL LIMIT.—Proportional limit (abbreviated P-limit) is the stress at which deformations cease to be proportional to the load. This point is determined by plotting a stress-strain or load-deformation curve. This definition holds both for tensile and transverse strength measurements.

MODULUS OF RUPTURE.—Modulus of rupture is the maximum stress in the extreme fiber—that is, outer surface—of a specimen tested to rupture by a transverse force, as computed by the empirical application of the flexure formula to stresses above the transverse proportional limit.

Modulus of rupture (sometimes called maximum fiber stress) =

$$\frac{3\ P\ L}{2\ b\ d^2}, \tag{7}$$

where the letters refer to the same terms as below.

MODULUS OF ELASTICITY.—Modulus of elasticity (transverse) is the ratio of unit stress within the proportional limit to the corresponding unit strain.

$$\text{Modulus of elasticity (transverse)} = \frac{L^2\ S}{6df}, \tag{8}$$

$$= \frac{PL^3}{4bd^3f},$$

where P = load in pounds (concentrated at center),
b = width of sample in inches,
d = thickness of sample in inches,
f = deflection at center in inches,
S = unit stress,
L = length of span in inches.

BRINELL HARDNESS NUMERAL.—Brinell hardness numeral (abbreviated B. h. n.) is the ratio of the pressure on a sphere used to indent the material to be tested to the area of the spherical indentation produced. The standard sphere used is a 10 mm diameter hardened steel ball. The pressures as chosen for tests on these materials are 500 kg for the harder materials and 250 kg for softer materials, and the time of application of pressure is 30 seconds. Five hundred (500) kilogram pressure was used in all regular tests recorded in this paper.

$$\text{B. h. n.} = P \div \pi\, tD = P \div \left[\pi D \left(D/2 - \sqrt{D^2/4 - d^2/4}\right)\right] \qquad (9)$$

P = pressure in kilograms,
t = depth of indentation,
D = diameter of ball,
d = diameter of indentation,

all dimensions being expressed in millimeters.

SHORE SCLEROSCOPE HARDNESS.—Shore scleroscope hardness is the height of rebound of a diamond-pointed hammer falling by its own weight on the object to be tested for hardness. The value is measured on an empirical scale on which the average hardness of martensitic high-carbon steel equals 100. On very soft materials a "magnifier" hammer is used in place of the commonly used "universal" hammer, and values may be converted to the corresponding "universal" value by multiplying the reading by 4/7. The scleroscope hardness when accurately determined is an index of the tensile elastic limit of the material tested.

IMPACT STRENGTH.—Impact strength is defined as the mechanical energy absorbed by a standard test piece during fracture by a blow from a pendulum hammer.

PERMANENT DISTORTION.—Permanent distortion is here defined as the permanent set or distortion due to a certain dead weight centrally suspended from a sample of known dimensions supported by V blocks with a definite separation. The natural distortion or warp of a few sheets of insulating material has been considered under this head.

MACHINING QUALITIES.—Machining qualities are not capable of rigorous definition. In this work they are considered to be given by the ease of machining, surface finish of machined samples, effect on machine tools for specimens sawed, turned, machine and

die threaded, tapped, drilled, and shaped, according to the arbitrary tests outlined in the Bureau publication mentioned on page 506. The results of such tests are largely determined by the personal judgment of the machinist.

4. DEFINITIONS OF THERMAL AND CHEMICAL PROPERTIES

THERMAL EXPANSIVITY.—Thermal expansivity of a solid material is the increase in length per unit length per degree centigrade rise in temperature.

HEAT EFFECTS.—The heat effects determined here were merely the effects of the application of heat over a range of 100 to 500° C. The approximate temperature at which blistering, cracking, and charring begin was recorded.

EFFECTS OF CHEMICALS.—The chemical effects determined in this work were the effects on 5 by 10 by 1.27 cm samples of laminated phenolic insulating materials when immersed in a 22 per cent (by weight) solution of sulphuric acid or a 17 per cent (by weight) solution of sodium hydroxide (caustic soda) for 48 hours. The following effects were considered: Visible effects (swelling, splitting, etc.), increase or decrease in weight, and change in hardness.

IV. TABULATION OF RESULTS

1. PRINCIPAL ELECTRICAL AND MECHANICAL PROPERTIES

The four ensuing data sheets give in a condensed form the results of many determinations. The methods of securing the data are given in a separate publication entitled "Methods of Measurement of Properties of Electrical Insulating Materials" and the final results are analyzed below. The arrangement and abbreviations have been explained in part. The notes collected below, however, make the four data tables independently complete.

Column 1 specifies material, grade, color, and surface finish.

Column 2 gives the identification number assigned the sample when received.

Column 5 gives the dates on which the phase difference ($\psi°$) and dielectric constant (K) determinations were made.

Columns 6–11, inclusive, give values of phase difference and dielectric constant at the lower and maximum wave lengths used on that day. Usually such determinations were made at five or more different wave lengths. The temperature and relative humidity of the air near the sample was measured. The values are on record in the radio laboratory and have not been given here.

The statement, "sample baked (date)," appears several times in these columns. The average time of baking was 96 hours and the temperature about 80° C.

Columns 13 and 14 are somewhat irregular, in that some measurements of surface resistivity were made at 34 per cent relative humidity instead of 25 per cent and some at 42 per cent instead of 50 per cent.

Column 17. These values were determined on samples 5 by 10 cm by the thickness stated in columns 3 and 4 (see pp. 524 to 533).

Columns 18 and 20. Where x and y appear with values of ultimate strength or modulus of rupture, it means that one value was obtained on a sample cut out the way of the grain and the other in a direction 90 degrees from the first. It is to be pointed out that where more than two values of tensile strength are given for test pieces cut from one sample one test piece marked x of any pair may not have been cut in the same direction as a test piece marked x in another pair. The test specimens marked x in the tensile strength column are not necessarily cut in the same direction as a modulus of rupture test specimen marked x.

Columns 22 and 23. The letters B and S refer to Brinell method and Shore scleroscope method, respectively. A and B refers to side of sample tested. Values of the A side only are given unless the A and B values differ appreciably. Thus, B–42–A means Brinell hardness numeral of 42 on side A.

The results condensed into these four large tables are given more fully in the graphs and tables of data on particular properties that follow.

TABLE 5.—Detailed Electrical and Mechanical Data on 20 Samples of Bakelite-Dilecto, Grades XX, X, and CB

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numerals for specimens tested at—	
												25 or 34 per cent [a]	42 or 50 per cent [b]	84 per cent			Ultimate strength	Modulus of elasticity÷1000	Modulus of rupture	Modulus of elasticity÷1000	20–30° C	50° C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		cm	In.		Meters	Deg.		Meters	Deg.		Ohm-cm×10^8	Ohms ×10^8	Ohms ×10^8	Ohms ×10^8	g/cm³	Per cent	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²		
XX. Blk., pol.	10	0.32	1/8	Mar. 14, 1918	779	2.0	4.5	792	1.8	4.6												
				Apr. 30, 1919	1265	1.9	5.1	4170	1.7	5.2												
	11	.64	1/4	Mar. 14, 1918	414	2.2	4.9	1375	1.9	5.0	7 700	11 000	[b] 4 000	3	1.35	0.44	15 200		15 400	1290		
											3 000	680	230	10			15 500					
XX. Nat., pol.	56	.64	1/4	Apr. 10, 1919	1004	1.9	5.3	3365	1.6	5.4	200	4 200	700	9			13 900	1510	19 000	1290		
				Apr. 16, 1919	5320	1.5	5.4															
	56–0	.64	1/4	May 3, 1919	952	1.7	5.3	3135	1.4	5.4	70 000	430 000	[b] 7 000	8	1.34	.25						
XX. Blk., pol.	57	.64	1/4	Nov. 5, 1918	654	2.4	5.3	3188	2.4	5.5					1.35	.32						
	162	.64	1/4	Apr. 1, 1919	979	2.5	5.3	3225	2.5	5.4	10 000	380	65	12	1.33	.20	13 500x		16 500x			
																	11 100y		15 600y			
	12	.95	3/8	Mar. 15, 1918	550	2.2	5.2	1140	2.0	5.3							14 300		20 700	1340	B–42–A	B–37–A
																	13 000				S–87–A	S–82–A
	14	.95	3/8	Mar. 16, 1918	557	2.1	5.3	1142	1.9	5.4	18 000	32 000	[b] 9 000	16	1.34	.17	11 000x				B–41–A	B–37–A
				Oct. 15, 1918	541	2.3	5.2	1930	2.3	5.4	22 000	20 000	[b] 7 500	11			12 600y				S–90–A	S–85–A
											5 000	1 700	600	12								
											5 000	4 400	1 800	18								
	13	1.27	1/2	Mar. 15, 1918	495	2.5	5.4	1450	2.4	5.6	2 000	17 000	13 000	140	1.35	.10	10 600x				B–40–A	B–39–A
																	11 000y				S–87–A	S–87–A
	59	1.27	1/2	Apr. 23, 1919	729	2.5	5.7	2394	2.3	5.9	1 000	3 600	1 800	120	1.34	.22	9 600		16 000			
																	11 900					
XX. Nat., po.	163	1.27	1/2	Mar. 27, 1919	726	2.0	5.5	2364	1.6	5.6	80 000	18 000	1 400	200	1.36	.14	14 400x		17 300y			
																	13 900y					
XX. Blk., pol.	251	1.27	1/2	June 10, 1919	721	2.1	5.6	1714	2.0	5.7	20 000	13 000	2 100	26	1.37	.19						

XX. Nat., pol.	60	.64	1/4	June 7, 1918	1355	1.8	5.6	3215	1.3	5.7	600 000	500	60	3	1.37	1.70	13 600						
				Sept. 19, 1918	682	2.4	5.5	2900	1.8	5.8							13 600						
				Oct. 19, 1918	683	2.2	5.6	3280	1.7	5.7													
				Dec. 17, 1918[c]	1597	1.5	5.0	3788	1.2	5.1													
				Jan. 10, 1919	734	1.8	4.9	3775	1.3	5.1													
	164	.64	1/4	Apr. 1, 1919	942	2.0	4.9	3080	1.6	5.0	12 000	[a] 7 200	3 700	6	1.30	3.00	23 300x		27 100x				
				July 22, 1919	649	2.2	5.1	3000	1.7	5.2	11 000	[a] 11 000	6 000	12			11 500y		16 900y				
											1 700	5 300	2 100	6									
											14 000	7 200	2 700	4									
	61	.95	3/8	June 17, 1918	1960	1.6	5.6	3290	1.4	5.7	950 000	2 500 000	[b]12 000	4	1.37	.73	15 000x	1580	34 100	2370	B–34–A	B–31–A
				Sept. 20, 1918	876	2.0	5.6	1147	2.0	5.6	1 000 000	3 400	400	4			22 700y	2720			S–73–A	S–65–A
				Oct. 29, 1918	832	2.3	5.5	1154	1.9	5.6													
				Nov. 13, 1918[d]	545	2.1	5.2	1932	1.7	5.4													
	165	.95	3/8	Apr. 2, 1919	819	2.1	5.5	2698	1.6	5.7	420 000	18 000	7 300	21	1.37	.74	11 000x		16 200x				
																	25 600y		23 300y				
	62	1.27	1/2	June 12, 1919	532	2.0	5.6	1940	1.6	5.7	280 000	980 000	[b] 5 000	4	1.31	2.20	14 300x	1500	21 600	1440	B–23–A	B–20–A
				Jan. 23, 1920	594	2.2	5.5	2228	1.7	5.6	1 000 000	1 200	200	3			22 900y	2740			S–64–A	S–63–A
	63	2.54	1														14 600x	1410					
																	22 200y	2720					
C. B. Nat., pol.	166	.64	1/4	Mar. 5, 1919	1240	3.7	5.2	3100	3.8	5.4	200	100	9	1	1.32	.46	10 300y		13 600				
																	8 400x		13 700				
																	9 800y		14 200				
																	8 800x						
																	10 200y						
																	8 800x						
	175	1.27	1/2												1.29	.52	8 400x		13 400		B–37–A	B–34–A	
																	7 600x		13 600		B–28–B	B–25–B	
																					S–70–A	S–70–A	
																					S–47–B	S–46–B	

[a] All values marked [a] are at 34 per cent; all others at 25 per cent.
[b] All values marked [b] are at 42 per cent; all others at 50 per cent.
[c] Sample baked Dec. 17, 1918.
[d] Sample baked Nov. 13, 1918.

TABLE 6.—Detailed Electrical and Mechanical Data on 25 Samples of Bakelite Micarta, Grades 32-X, 21-X, 323, 213, and 21-D

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of —			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numerals for specimens tested at—	
												25 per cent	42 or 50 per cent [a]	84 per cent			Ultimate strength	Modulus of elasticity÷1000	Modulus of rupture	Modulus of elasticity÷1000	20–30° C	50° C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		cm	In.		Meters	Deg.		Meters	Deg.		Ohm-cm×10^{13}	Ohms. ×10^{8}	Ohms. ×10^{8}	Ohms ×10^{8}	g/cm^3	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}		
32-X. Blk., pol	18	0.32	1/8	Mar. 24, 1918	655	2.7	5.2	1510	2.5	5.3												
				May 1, 1919	1377	2.8	5.4	4535	3.0	5.6												
	19	.64	1/4	Mar. 18, 1919	774	2.9	5.6	1894	2.9	5.8	200	460	340	40	1.35	0.45	8 900x		16 000	1470		
																	12 600y					
	146	.64	1/4	Oct. 21, 1918	696	4.3	6.0	3482	5.3	6.5	40	300	120	28	1.35	.36	9 700x		14 200x			
				Mar. 4, 1919	1376	3.7	6.0	3420	3.9	6.2							11 400y		19 000y			
				Mar. 11, 1919[b]	1264	2.2	4.9	3097	2.1	5.0												
				Aug. 2, 1919	677	2.8	5.5	1842	2.8	5.7												
				Aug. 2, 1919	3326	2.8	5.8															
32-X. Blk., dull	147	.64	1/4	Mar. 21, 1919	1370	3.2	5.8	3370	3.3	5.9					1.35	.31	12 500x		17 500x			
																	9 500y		14 200y			
21-X. Nat., pol	252	.64	1/4	Aug. 1, 1919	832	2.0	5.7	1860	1.9	5.8	37 000	21 000	5300	44	1.35	.54						
				Aug. 1, 1919	3318	2.0	5.9															
32-X. Blk., pol	20	.95	3/8	Mar. 23, 1918	595	2.9	5.7	1190	3.1	5.8	45 000	2 600	820	21			12 900x		14 400	1050	B–39–A	B–34–A
																	9 800y					
	148	.95	3/8	Apr. 2, 1919	850	3.8	5.8	2845	4.3	6.1	30	60	16	4	1.34	.38	11 800x		13 300x			
											64	410	59	3			9 600y		17 300y			
	253	1.27	1/2	June 11, 1919	728	2.2	5.8	1736	2.1	6.0	1 000	3 600	680	15								
	21	1.27	1/2	Mar. 18, 1919	750	2.8	6.2	1840	2.8	6.3	1 200	1 200	[a] 400	6	1.36	.28	8 800x				B–39–A	B–34–A
											500	160	70	4			12 200y				S–83–A	S–80–A
21-X. Nat., pol	149	1.27	1/2	Mar. 31, 1919	740	2.7	5.8	2440	2.5	6.0	200	1 600	1 000	70	1.35	.19	9 800x		16 800x			
											2 000	3 000	400	12			12 800y		18 000y			

323. Blk., pol.	24	.32	1/8	Mar. 24, 1918	655	2.3	5.2	1505	1.9	5.3												
				May 2, 1919	1413	2.3	5.8	4650	2.1	5.9												
	25	.64	1/4												1.38	1.50						
	150	.64	1/4	Sept. 28, 1918	1080	3.5	6.4	3188	4.2	6.7	30	66	9	1	1.37	.85	18 100x		23 300	2065		
				Oct. 22, 1918	709	3.5	6.3	3520	4.3	6.8							12 600y		17 900y			
				Aug. 1, 1919	885	3.4	6.4	3520	3.9	6.7												
321. Blk., dull	151	.64	1/4	Mar. 24, 1919	1420	2.4	6.0	3502	2.5	6.2					1.37	.63	21 300x		25 300x			
				Oct. 10, 1919	431	3.1	6.2	1070	3.0	6.4							13 600y		18 700y			
				Oct. 10, 1919	1461	3.1	6.5	2217	3.1	6.6												
				Oct. 10, 1919	3598	3.1	6.6															
213. Nat., pol.	254	.64	1/4	Aug. 2, 1919	692	2.1	5.8	3358	1.7	6.0	93 000	21 000	4 700	33	1.37	1.38						
Probably 213. Nat., pol.	15	.64	1/4								34 000	14 000	a 5 000	9	1.36	1.10						
				Mar. 18, 1918c	430	2.5	5.3	1410	2.0	5.6	67 000	21 000	a 6 300	5								
323. Blk., pol.	26	.95	3/8	Mar. 23, 1918	600	2.2	5.7	1185	2.1	5.8					1.37	1.21	19 500y		18 800	1150	B-35-A	B-33-A
																					S-83-A	S-78-A
	152	.95	3/8	Apr. 2, 1919	857	2.6	6.1	2832	2.4	6.3	900	30	5	1	1.37	.57	12 500x		16 300x			
											170	13 000	200	3			17 500y		18 900y			
	27	1.27	1/2	Mar. 18, 1919	606	2.4	6.3	1481	2.1	6.4	32 000	8 800	a 3 000	9	1.38	1.04	14 500x				B-34-A	B-30-A
											6 000	360	80	2			16 900y				S-79-A	S-75 A
213. Nat., pol.	153	1.27	1/2	Apr. 2, 1919	739	2.1	5.8	2415	1.8	6.0	8 000	11 000	8 000	300	1.36	.30	15 300x		20 800x			
											128 000	8 800	3 400	35			20 300y		30 900y			
323. Blk., pol.	265	1.27	1/2	June 11, 1919	730	2.2	5.8	1745	2.0	5.9	29 000	25 000	5 900	9								
21-D. Nat., pol.	182	.64	1/4	Mar. 6, 1919	1395	5.2	6.4	3511	5.7	6.7					1.36	1.09	6 900x		13 900			
																	9 500y		14 400			
																	10 100y					
																	6 700x					
21-D. Nat., pol.	183	.95	3/8	Apr. 28, 1919	1225	4.6	6.6	2920	4.9	6.9												
	184	1.27	1/2	Apr. 29, 1919	1126	6.3	5.9	2688	7.1	6.2					1.36	.74	9 000x		12 900		B-36-B	B-30-B
																	10 100y		14 500		S-68-A	S-64-A
																	9 400x				S-72-B	S-66 B
																	9 300y				B-36-A	B-30-A
	169	1.27	1/2								100	580	130	3							B-38-A	B-35-A
																					B-38-B	B-36-B
																					S-79-A	S-75-A
																					S-80-B	S-75-B

a All values marked (a) are at 42 per cent; all others at 50 per cent.

b Sample baked Mar. 11, 1919.

c Bought in open market.

TABLE 7.—Detailed Electrical and Mechanical Data on 16 Samples of Condensite Celoron, Grades 10, 15, and 20

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numerals for specimens tested at—	
												25 per cent	50 per cent	84 per cent			Ultimate strength	Modulus of elasticity÷1000	Modulus of rupture	Modulus of elasticity÷1000	20–30° C	50° C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		cm.	In.		Meters	Deg.		Meters	Deg.		Ohm-cm×10⁸	Ohms ×10⁸	Ohms ×10⁸	Ohms ×10⁸	g/cm	Per cent	Lbs./in.²	Lbs./in.²	Lbs./in.²	Lbs./in.²		
15. Blk., pol.	141	0.32	1/8	Apr. 24, 1918	1435	2.2	5.8	4700	2.0	5.9							15 300y					
																	7 600x					
																	14 500y					
																	7 500x					
	142	.64	1/4	Apr. 28, 1919	870	2.2	6.0	2855	1.9	6.0	10 000	25 000	360	40	1.39	0.35	12 500x		13 000			
				Oct. 8, 1919	700	2.5	6.0	1412	2.3	6.1							7 900y		12 500			
				Oct. 8, 1919	2410	2.3	6.2	3412	2.1	6.2							6 900y		19 000			
																	11 800x					
10. Nat., pol.	160	.64	1/4	Oct. 18, 1918	694	3.2	5.8	3430	3.4	6.2	200	7 000	1 200	150	1.40	.36	10 100		13 300			
15. Blk., pol.	186	.64	1/4	Dec. 20, 1918	1720	2.6	5.6	3963	2.1	5.8	4 500	6 200	1 200	14	1.41	.32	16 500x		21 400x			
																	9 100y		15 100y			
10. Nat., pol.	187	.64	1/4	Mar. 29, 1919	1037	2.5	6.2	3425	2.5	6.3	3 100	18 000	1 800	33	1.41	.24						
	106	.64	1/4	Aug. 12, 1918	1205	3.3	7.0	2795	4.1	7.2												
15. Blk., pol.	273A	64	1/4	Jan. 22, 1920	508	4.7	7.2	3545	5.5	7.9												
	143	.95	3/8	Apr. 28, 1919	853	2.4	6.0	2800	2.3	6.2							6 600y		9 900x			
																	15 100x		17 600y			
																	6 900y		17 000y			
																	14 600x					
	188	.95	3/8	Dec. 20, 1918	1495	1.9	5.8	3462	1.9	6.2					1.43	.24	8 500x		11 800x			
				Oct. 7, 1919	623	3.1	6.8	3800	2.7	7.1							14 900y		18 600y			

	144	1.27	½	Aug. 5,1919	753	2.5	6.4	2613	2.4	6.6	9 000	8 000	6 000	220	1.38	.26	8 500y	.....	11 600	.....	B–38–A	B–34–A
																	13 800x	.....	8 200	.....	B–39–B	B–36–B
																	8 000y	.....	11 500	.....	S–85–A	S–82–A
																	14 500x	.....	.....	.....	S–86–B	S–81–B
10. Nat., pol.	161	1.27	½	Mar. 31,1919	744	2.7	5.9	2465	2.5	6.2	60	700	70	20	1.41	.20	8 400	.....	.....	.....	.....	.....
																	13 000	.....	.....	.....	.....	.....
15. Blk., pol.	272	1.27	½	Jan. 22,1920	678	4.7	7.9	2869	5.2	8.2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	189	1.27	½	Mar. 29,1919	768	2.6	6.3	2485	2.2	6.5	68 000	25 000	4 400	50	1.42	.18	16 200x	.....	22 100x	.....	.....	.....
																	9 400y	.....	22 800x	.....	.....	.....
10. Nat., pol.	145	3.02	1 1/16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	17 300x	.....	16 200	.....	.....	.....
																	17 300x	.....	18 500	.....	.....	.....
																			18 500	.....	.....	.....
20. Nat., pol.	218	.64	¼	Jan. 15,1919	1665	5.8	6.4	4075	6.9	7.0	100	.....	280	25	1.34	.32	7 900x	.....	12 000	.....	.....	.....
											27	1 800	270	2	.....	.....	8 500y	.....	12 000	.....	.....	.....
	219	1.27	½	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.35	.46	7 800x	.....	12 000	.....	B–34–A	B–32–A
																	7 200y	.....	8 400	.....	B–42–B	B–33–B
																					S–88–A	S–84–A
																					S–87–B	S–80–B

TABLE 8.—Detailed Electrical and Mechanical Data on 38 Samples of Formica, Grades M, M–2, P, and R

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numerals for specimens tested at—	
												25 per cent	42 or 50 per cent [a]	84 per cent			Ultimate strength	Modulus of elasticity ÷ 1000	Modulus of rupture	Modulus of elasticity ÷ 1000	20–30°C	50°C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		cm.	In.		Meters	Deg.		Meters	Deg.		Ohm-cm×10^8	Ohms ×10^8	Ohms ×10^8	Ohms ×10^8	g/cm^3	Per cent.	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}		
M. Nat., pol.	9	0.16	1/16	Mar. 12,1918	525	2.4	5.1	1320	2.2	5.2												
				May 2,1919	2030	2.7	6.2	6760	3.0	6.4												
	6	.32	1/8	Mar. 4,1918	354	3.0	4.7	1410	2.9	5.0												
M. Blk., dull	211	.32	1/8	May 16,1919	1335	3.3	5.4	2563	3.5	5.6												
M. Blk., pol.	5	.64	1/4	Mar. 4,1918	1025	3.2	5.3	1093	3.2	5.5												
				Sept. 20,1918	672	5.4	5.4	2585	7.1	6.4												
				Oct. 17,1918	707	5.7	6.1	3550	7.6	6.5												
				Oct. 25,1918[b]	664	3.8	5.2	3240	4.0	5.6												
				Mar. 25,1919	1002	3.7	5.3	3345	4.0	5.5												
				Sept. 20,1919	1064	6.0	6.1	3600	7.1	6.6												
	5–0	.64	1/4								6	40	12	3	1.37	0.69	11 100x		14 900	1120		
																	14 000y					
M. Blk., dull	212	.64	1/4	Dec. 18,1918	1535	2.4	4.1	3580	1.9	4.2	800	1000	400	50	1.36	.30	11 300x		18 800x			
				Jan. 18,1919	940	2.3	4.3	3138	2.0	4.4							14 900y		22 700y			
	167	.64	1/4	Sept. 30,1918	1340	2.7	5.3	2829	2.8	5.5	1100	1200		8	1.36	.39	11 300x		15 000			
											5800	740					9 700x		16 000			
																	11 000x		16 200			
	168	.64	1/4	Sept. 30,1918	1270	2.2	5.0	2675	2.4	5.3	1100	1300		7	1.37	.42	10 200x		15 900			
												520					10 300x		15 600			
																	10 300x		14 600			
M. Blk., pol.	101	.64	1/4	Aug. 15,1918	678	2.6	5.3	3052	2.9	5.5	30000	2700	700	13	1.36	.19	11 700x		17 100x			
											500	630	280	75			11 200y		17 700y			
	108	.64	1/4	Mar. 25,1919	965	2.6	5.1	3216	2.6	5.2	3600	470	120	1	1.38	.38						

M. Blk., dull	242	.64	1/4	Mar. 6, 1919	648	2.7	5.0	3143	2.7	5.3	1800	1200	130	3	1.34	.33						
				Mar. 26, 1919	955	2.6	5.1	3225	2.7	5.3												
M. Blk., pol	7	.95	3/8	Mar. 6, 1918	405	2.7	5.4	1460	2.7	5.6	60	70	16	4							B-35-A	B-33-A
				Sept. 16, 1919	1148	3.8	5.6	1490	3.9	5.7											S-84-A	S-80-A
				Sept. 29, 1918[c]	1126	3.0	5.8	2345	3.1	5.7												
				Apr. 23, 1919				2420	3.5	5.6												
	7-0	.95	3/8								480	460	[a]180	1					20 500	1420		
	111	.95	3/8	Sept. 23, 1918	1158	4.1	5.9	2005	4.2	6.0					1.38	.28						
M. Blk., dull	213	.95	3/8	Jan. 20, 1919	774	2.1	5.2	2642	2.0	5.3					1.36	.13	13 600x		16 100			
																	14 800y					
M. Blk., pol	8	1.27	1/2	Mar. 9, 1918	375	3.2	5.6	900	3.3	5.8					1.35	.23	11 200x				B-37-A	B-34-A
				Nov. 13, 1919	763	3.9	6.1	886	3.9	6.2							13 500y				S-85-A	S-79-A
M. Nat., dull	115	1.27	1/2	Aug. 5, 1919	594	3.4	6.0	736	3.3	6.1	200	90	18	3			10 900		18 000			
				.....do	1515	3.5	6.2	2577	3.5	6.3							10 600		18 600			
M. Blk., dull	214	1.27	1/2	Jan. 18, 1919	744	2.9	5.7	2443	2.9	5.8	80	260	80	20	1.35	.15	13 600x		16 900			
				Jan. 22, 1919	707	2.8	5.6	2368	2.9	5.8							13 400x		18 700			
	243	1.27	1/2	Feb. 25, 1919	983	2.3	4.8	2370	2.4	4.8	5000	1800	330	6								
M. Blk. pol	8-0	1.27	1/2								20	100	68	10								
											[d]10	48	40	6								
	3-0	2.54	1	Feb. 20, 1919	459	4.0	6.1	2756	3.3	6.1												
M-2. Blk., pol	50	.64	1/4	June 12, 1918	1400	4.6	5.9	3460	5.2	6.1					1.37	1.01	17 200	1720	20 000	1480		
	116	.64	1/4	Nov. 6, 1918	629	4.2	5.1	2830	5.4	5.5	30	60	7	2	1.32	.26	13 500x		17 900x			
																	10 900y		13 200y			
M-2. Nat., dull	140	.64	1/4	Mar. 31, 1919	1000	3.9	5.5	3306	4.5	5.8	20	140	23	3	1.34	.28						
M-2. Blk., pol	51	.96	3/8	June 19, 1918	1130	3.0	5.4	1950	3.2	5.6		410	120	4	1.37	.14	14 700				B-44-A	B-40-A
																	14 700				S-94-A	S-93-A
	117	.96	3/8	Nov. 12, 1918	[e]596	6.4	6.5	1690	9.9	7.3	20	72	18	2	1.29	1.38	14 900					
																	12 500x		15 200x			
				Nov. 18, 1918[f]	558	3.9	5.6	2000	5.0	5.9							6 670y		10 100y			
	52	1.27	1/2	Mar. 10, 1919	720	3.0	5.7	2766	3.2	6.0	330	100	[a]62	1	1.34	.29	11 000x	1730	22 600	1460		
											200	50	19	2			15 400y	1840				
M-2. Nat., dull	54	1.27	1/2	Aug. 4, 1919	602	2.7	4.1	870	3.6	4.1	1300	1200	[a]660	7	1.36	.19	15 100	1640	21 000	1310	B-45-A	B-42-A
				Aug. 5, 1919	1608	2.6	4.2	2135	2.6	4.2	700	800	520	40							S-86-A	S-85-A

[a] All values marked [a] are at 42 per cent; all other at 50 per cent.
[b] Sample baked Oct. 25, 1918.
[c] Sample baked Sept. 29, 1918.
[d] Surface sanded.
[e] Poorly laminated.
[f] Sample baked Nov. 18, 1918.

96422°—22——3

TABLE 8.—Detailed Electrical and Mechanical Data on 38 Samples of Formica, Grades M, M-2, P, and R—Continued.

Grade, color, and surface	B. S. sample number	Approximate thickness		Date of test	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Wave length (λ_m)	Phase difference (ψ)	Dielectric constant (K)	Volume resistivity	Surface resistivity at relative humidity of—			Density	Moisture absorbed	Tensile strength		Transverse strength		Hardness numerals for specimens tested at—	
												25 per cent	42 or 50 per cent	84 per cent			Ultimate strength	Modulus of elasticity ÷1000	Modulus of rupture	Modulus of elasticity ÷1000	20–30°C	50°C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		cm	In.		Meters	Deg.		Meters	Deg.		Ohm-cm×10^{8}	Ohms ×10^{8}	Ohms ×10^{8}	Ohms ×10^{8}	g/cm^3	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}	Lbs./in.^{2}		
M-2. Blk., pol.	118	1.27	½	Mar. 25, 1919	1017	3.8	6.0	2485	4.3	6.3	1200	950	180	7	1.37	.09	11 100		16 900			
																	12 000		16 900			
	216	1.27	½	Mar. 26, 1919	737	3.6	5.8	2444	3.8	6.1	470	1000	250	6	1.36	.23	14 100x		16 000x			
																	8 200y		12 600y			
	53	2.54	1														12 400x	2000				
																	15 200y	2830				
P. Nat., dull	103	.64	¼	Sept. 13, 1918	482	3.2	5.5	2500	3.6	6.3	90	600	200	50	1.38	.77	24 900x		17 800			
				Nov. 4, 1918	684	3.4	5.9	3412	3.7	6.2							12 100y		19 200			
																	24 900x		19 400			
																	11 100y					
P. Nat.	104	.95	⅜	Mar. 11, 1919	868	2.7	5.7	2745	2.4	5.8	600	220	65	3	1.41	.53	25 600y		29 900x			
																	27 800y		18 700y			
																	13 900x					
																	14 000x					
																	14 700x					
																	26 000x					
																	13 100y					
	55	1.27	½	June 19, 1918	1707	2.2	5.6				2000	1200	640	50	1.34	.28	15 000x	1520	21 100	1410	B-38-A	B-34-A
																	23 000y	3000			S-86-A	S-82-A
	215	1.27	½	Mar. 27, 1919	705	2.7	5.4	2275	2.7	5.6					1.36	.76	17 700x		27 000x			
																	12 200y		15 200y			
R. Nat.	172	.64	¼	Mar. 5, 1919	1400	4.2	6.4	3450	4.7	6.5	60	340	220	80	1.38	1.47	9 700x		13 300			
																	11 000y		13 400			
																	10 500y		14 700			
																	10 300x		14 700			

173	.95	3/8	....	......	......	....	......	......	......	....	....	....	......	1.37	1.38	9 000x	....	12 800	......	....	....
																9 900y	....	16 500	......	....	....
																6 700x	....	14 200	......	....	....
																9 800y	....	....	......	....	....
174	1.27	1/2	....	......	......	....	......	......	......	....	....	....	......	1.39	.81	10 300x	....	17 500	......	B-40-A	B-35-A
																10 600x	....	16 000	......	B-38-B	B-34-B
																				S-70.5-A	S-64-A
																				S-70.5-B	S-65-B

2. PHASE DIFFERENCE AND DIELECTRIC CONSTANT

The results of the measurements of phase difference and dielectric constant on representative samples are shown graphically in the following Figs. Nos. 2 to 27.

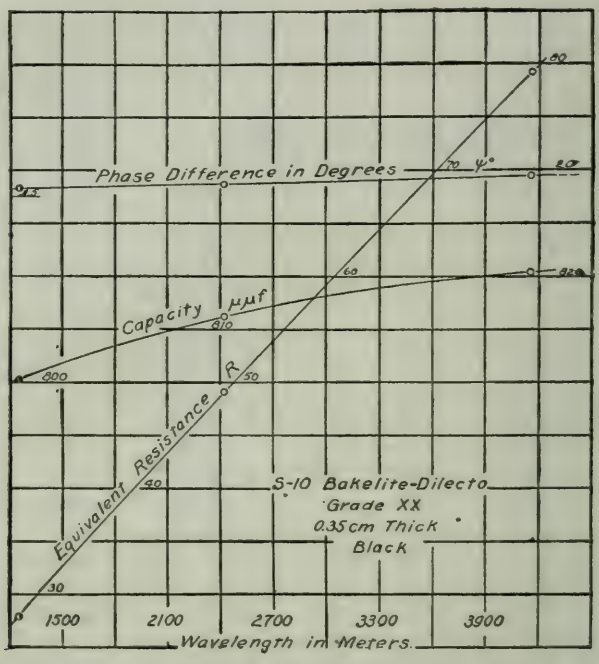

FIG. 2.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.35 cm thick*

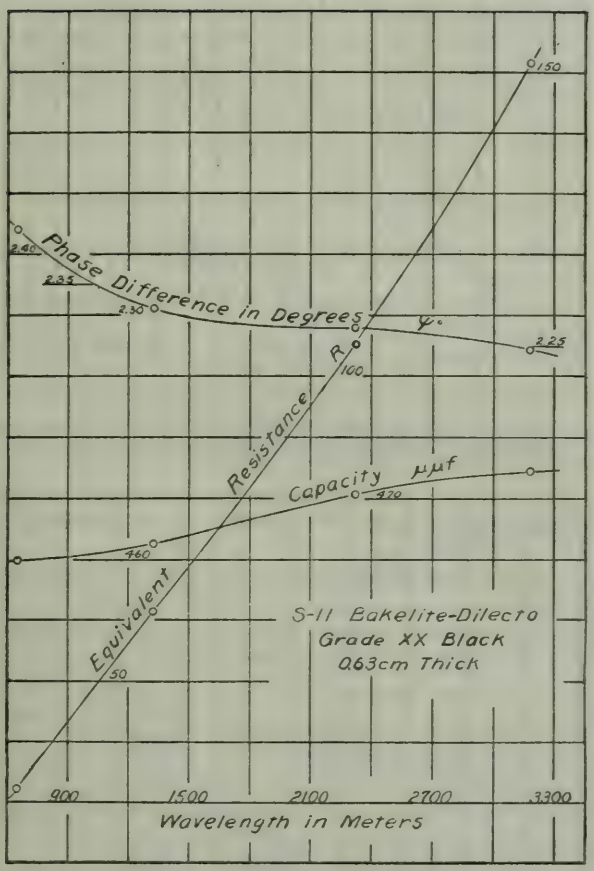

FIG. 3.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.63 cm thick*

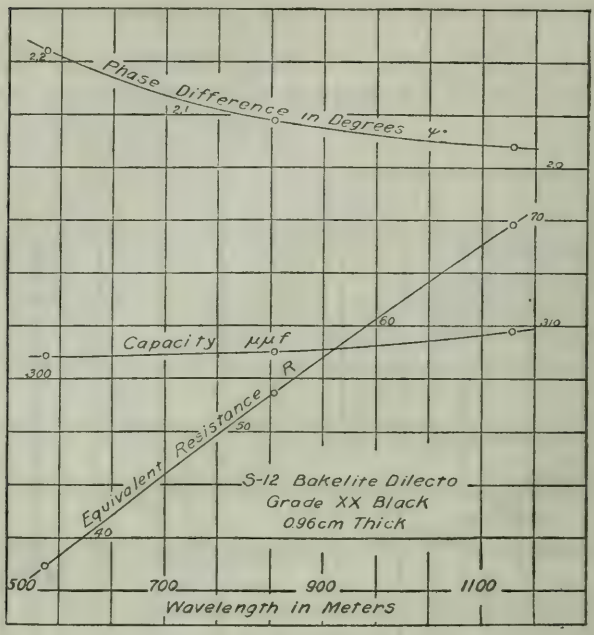

FIG. 4.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade XX, 0.96 cm thick*

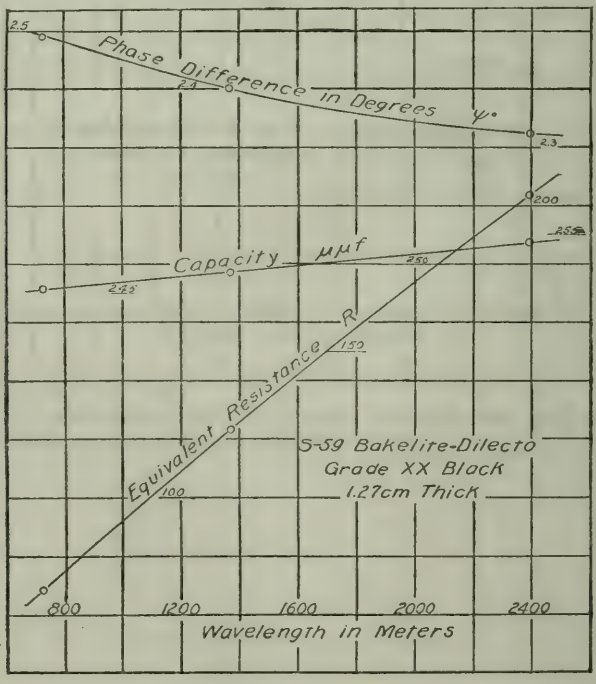

FIG. 5.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency of Bakelite-Dilecto, grade XX, 1.27 cm thick*

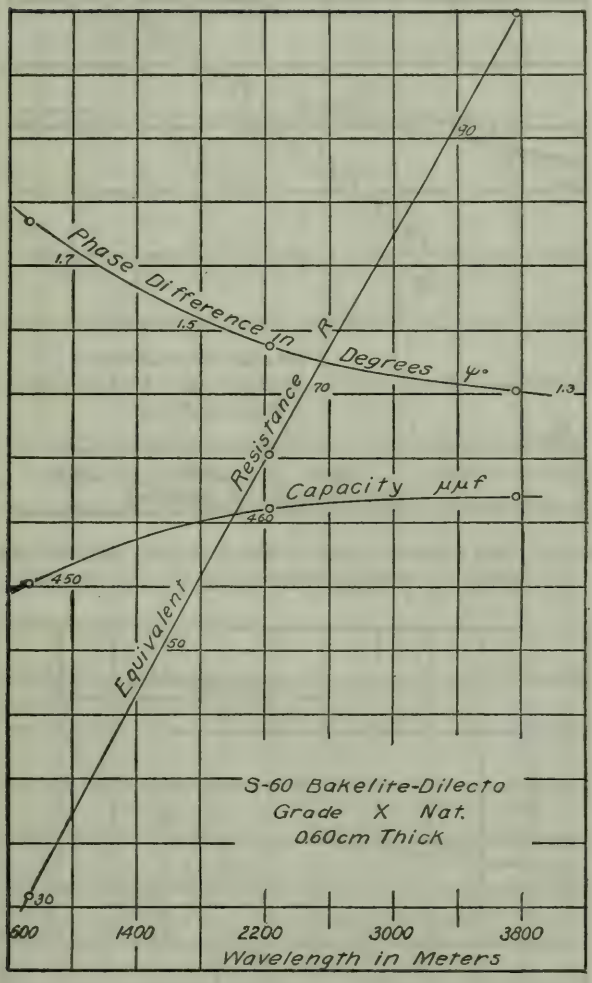

FIG. 6.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 0.60 cm thick*

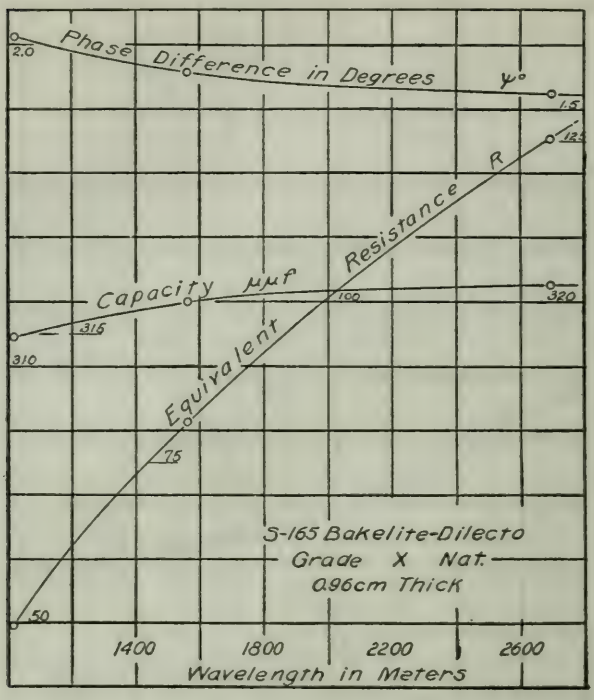

FIG. 7.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 0.96 cm thick*

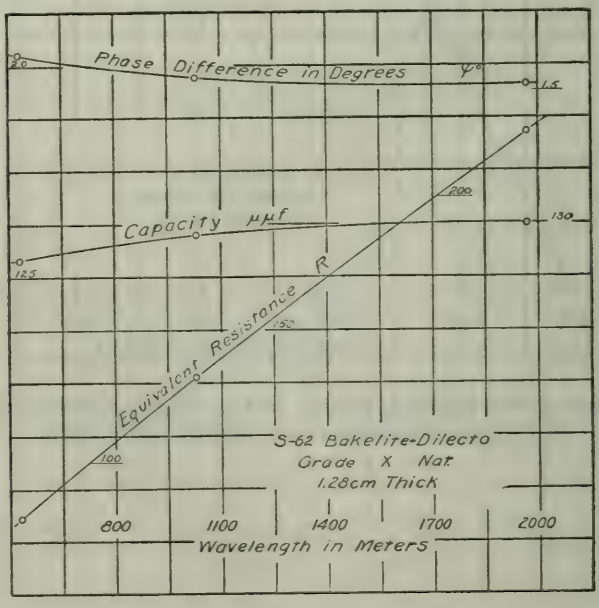

FIG. 8.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite-Dilecto, grade X, 1.28 cm thick*

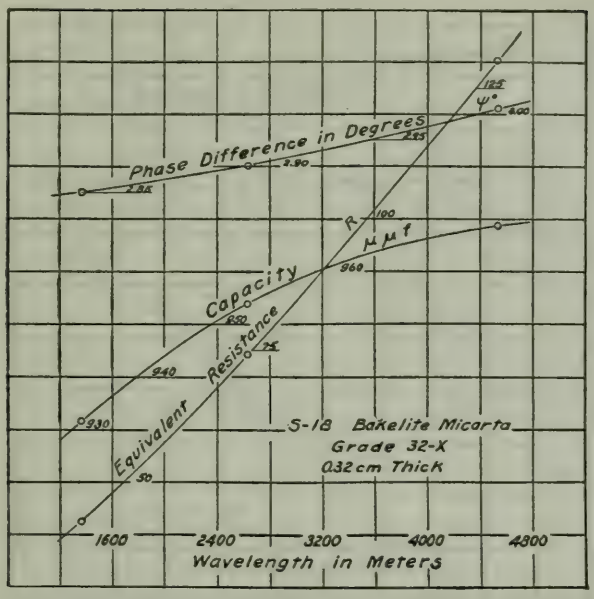

FIG. 9.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 32-X, 0.32 cm thick*

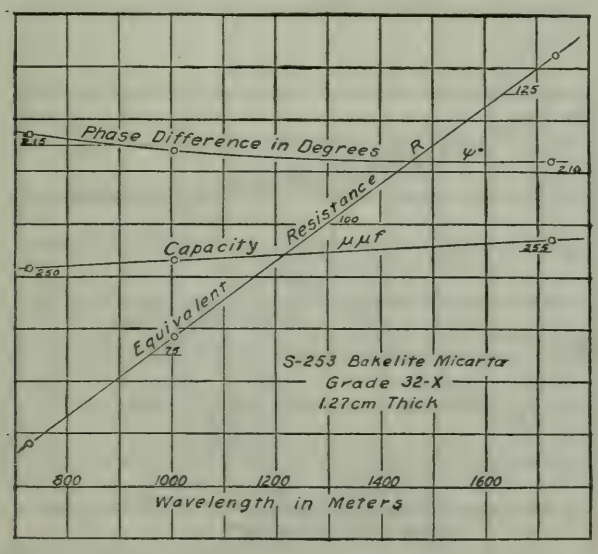

FIG. 10.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 32-X, 1.27 cm thick*

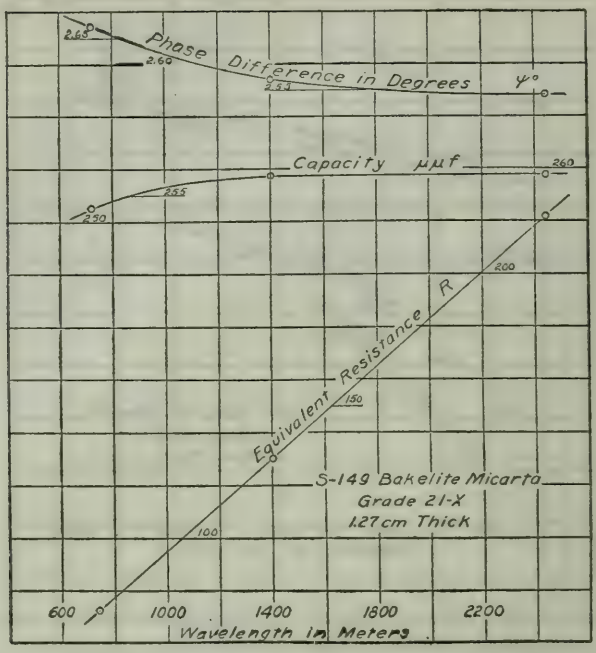

FIG. 11.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 21-X, 1.27 cm thick*

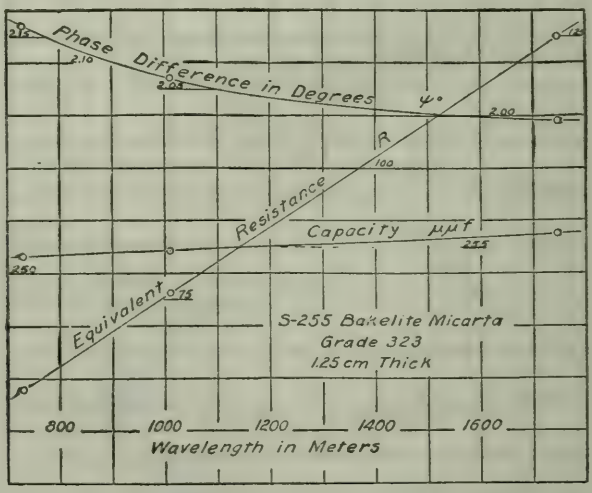

FIG. 12.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 323, 1.25 cm thick*

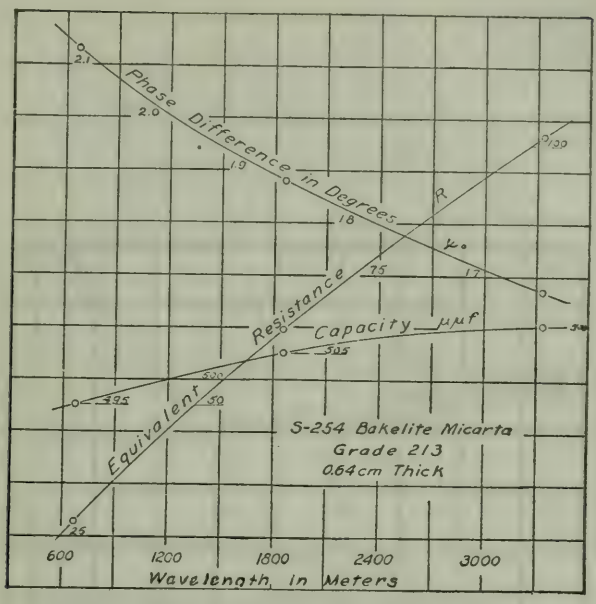

FIG. 13.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 213, 0.64 cm thick*

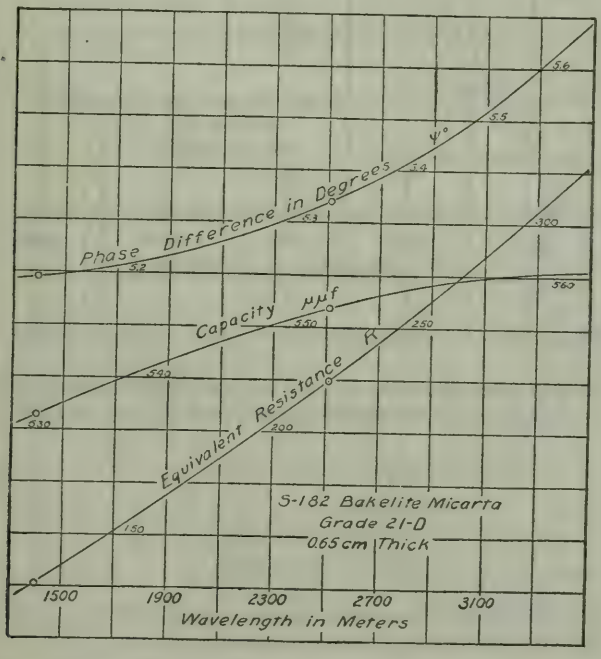

FIG. 14.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Bakelite Micarta, grade 21-D, 0.65 cm thick*

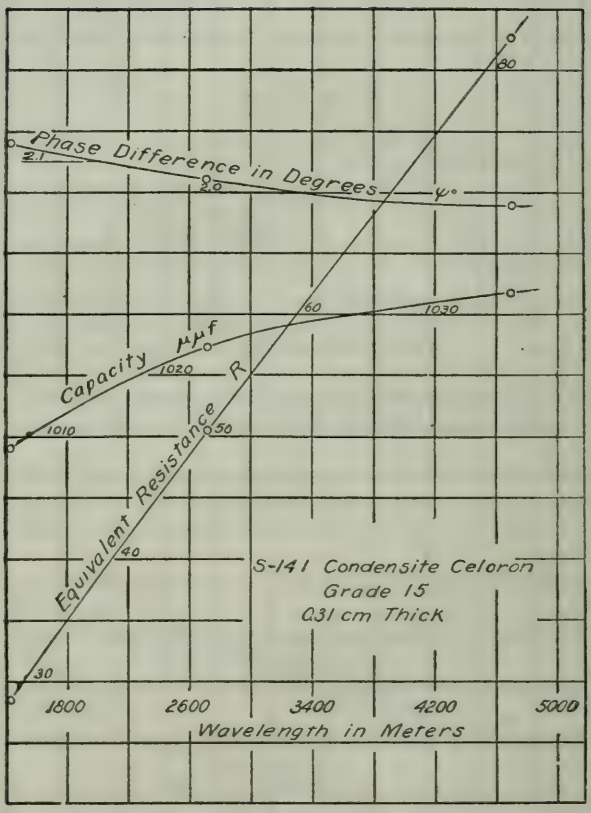

FIG. 15.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.31 cm thick*

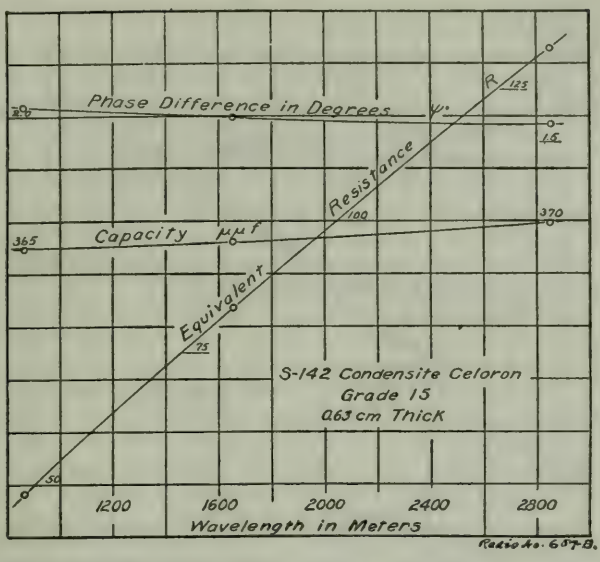

FIG. 16.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.63 cm thick*

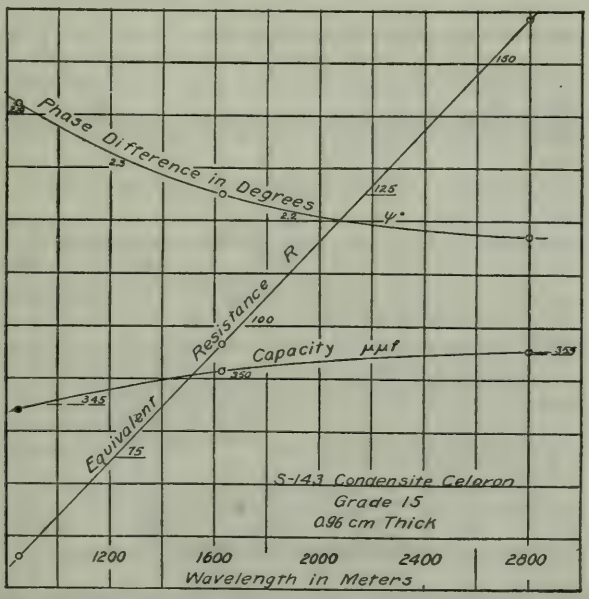

FIG. 17.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 0.96 cm thick*

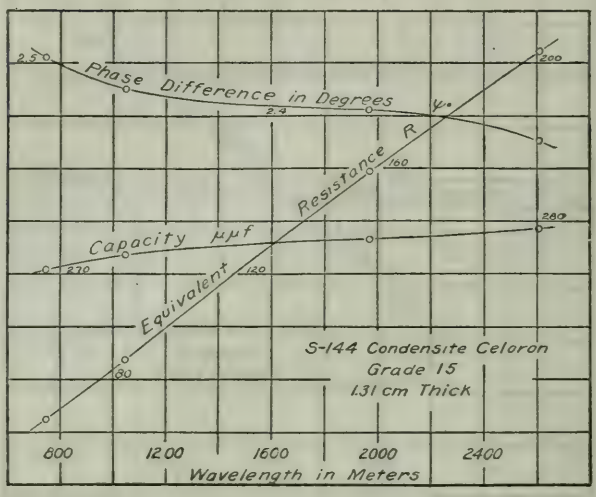

FIG. 18.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Condensite Celoron, grade 15, 1.31 cm thick*

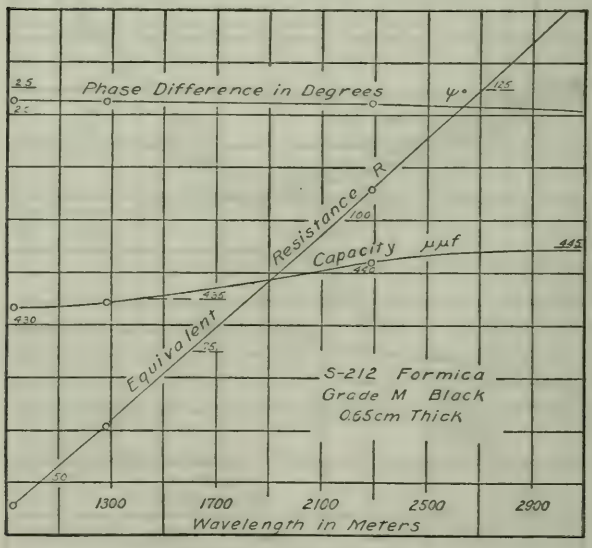

FIG. 19.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 0.65 cm thick*

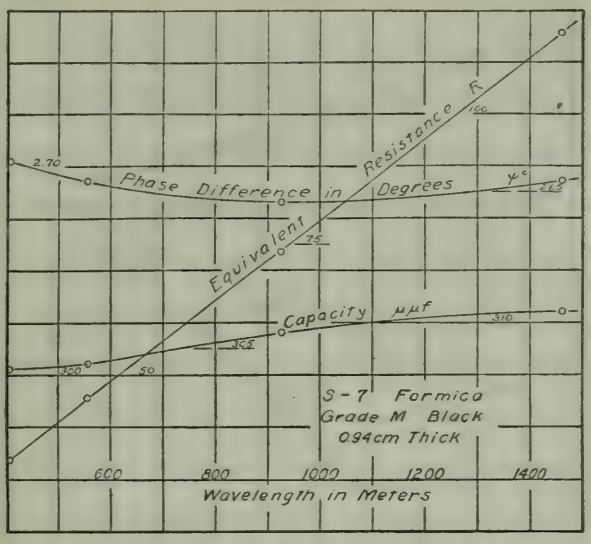

FIG. 20.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 0.94 cm thick*

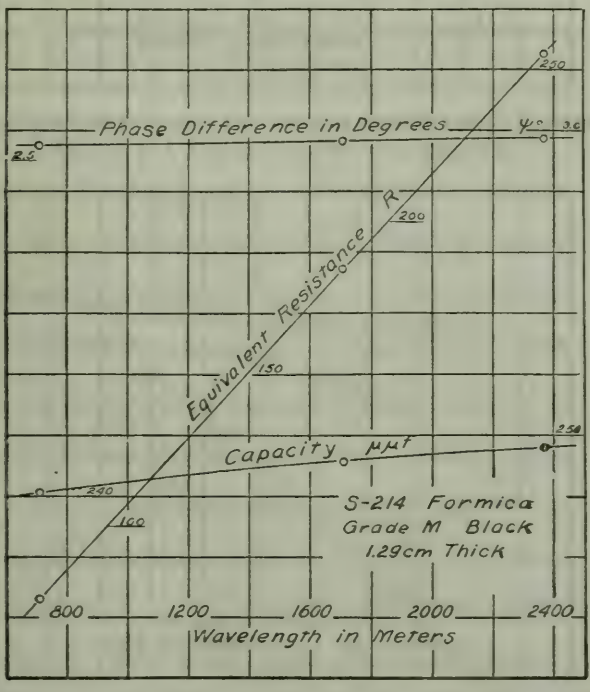

FIG. 21.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 1.29 cm thick*

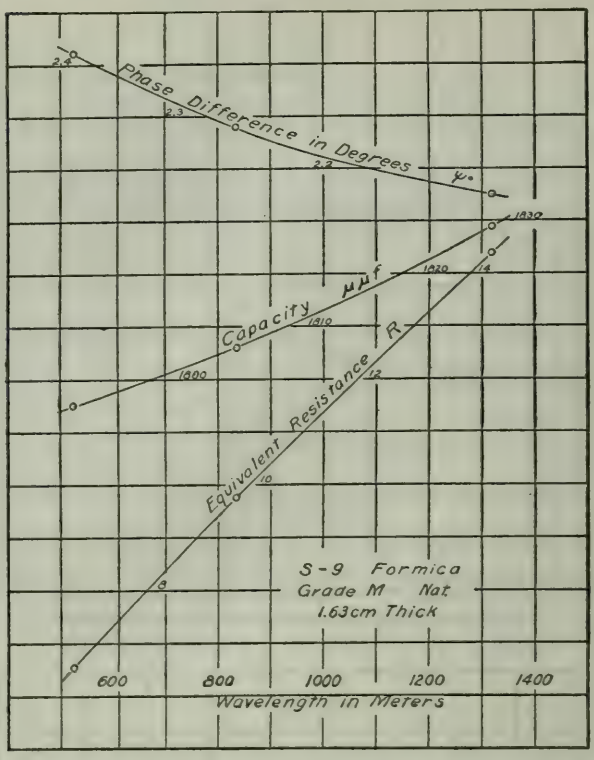

FIG. 22.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M, 1.63 cm thick*

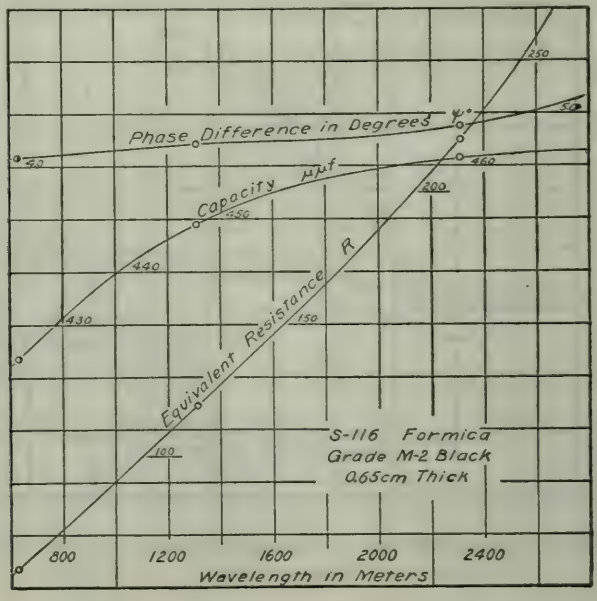

FIG. 23.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M-2, 0.65 cm thick*

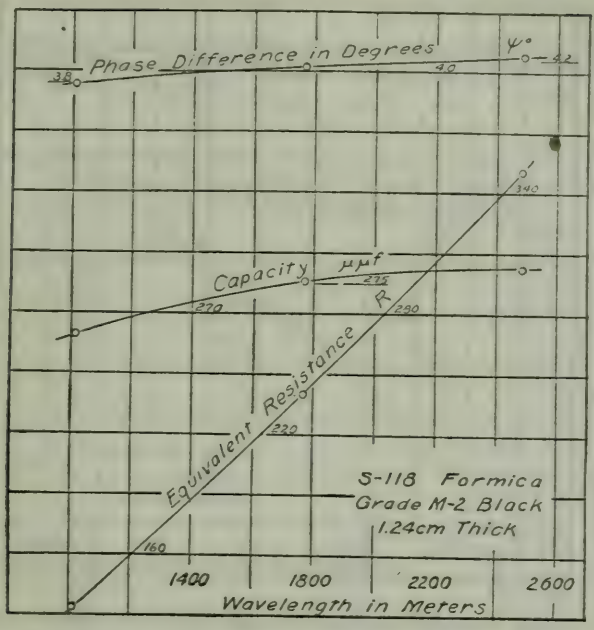

FIG. 24.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade M-2, 1.24 cm thick*

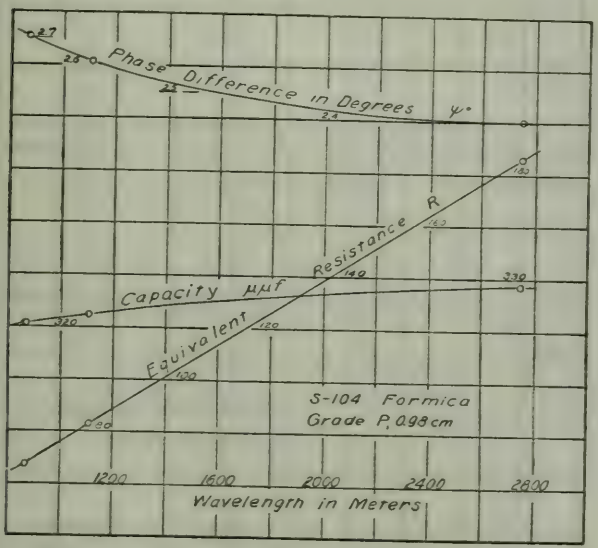

FIG. 25.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade P, 0.98 cm thick*

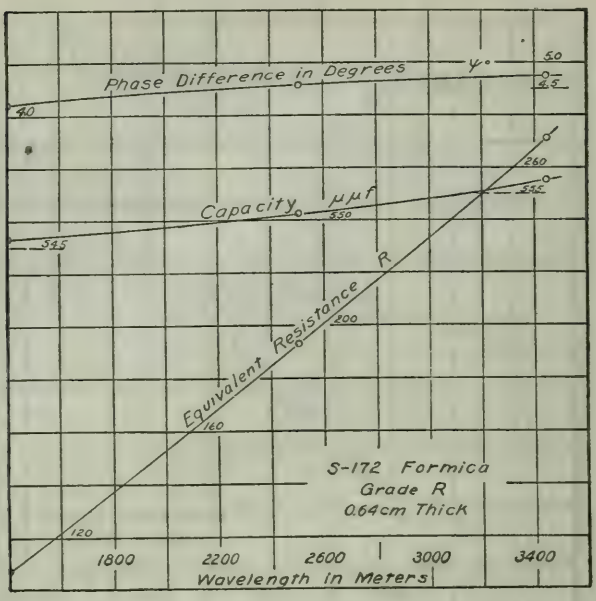

FIG. 26.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of Formica, grade R, 0.64 cm thick*

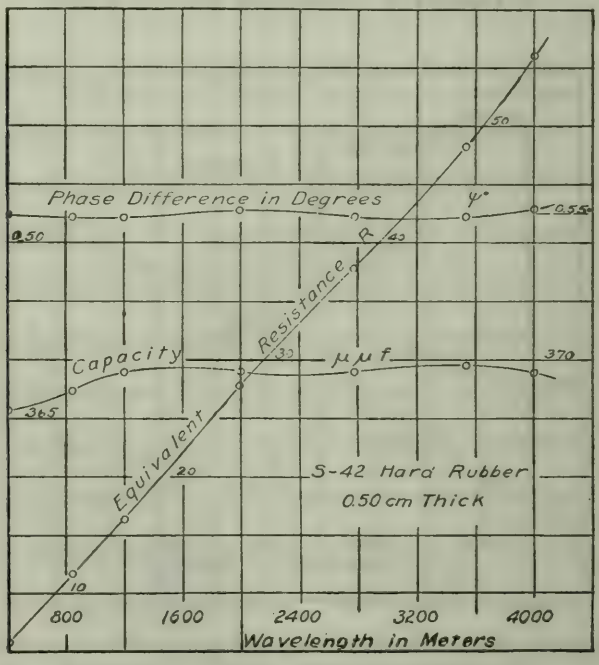

FIG. 27.—*Change of phase difference, capacity, and equivalent resistance with wave length or frequency, of hard rubber, 0.50 cm thick, sample taken from stock, grade unknown*

3. FLASH-OVER VOLTAGE AT RADIO FREQUENCIES

TABLE 9.—Suddenly Applied Radio-Frequency Voltage Necessary to Arc the Surface of the Several Grades of Phenolic Electrical Insulation between Two 2-cm Skirted Brass Studs Placed 2 cm Apart

Material	Grade	Color	Finish	B. S. sample number	Date of test	Flash-over voltage suddenly applied (E_f)
Bakelite-dilecto	XX	Black	Polished	11	July 23, 1918	17 700
	XX	do	do	11	Apr. 10, 1919	21 400
	XX	Natural	do	56–0	July 26, 1918	17 300
	XX	do	do	56–0	Feb. 12, 1919	20 000
	XX	Black	do	57	Feb. 11, 1919	22 200
	XX	do	do	162	Jan. 8, 1919	20 200
	X	Natural	do	60	July 29, 1918	17 900
	X	do	do	60	Jan. 18, 1919	20 600
	X	do	do	164	Feb. 17, 1919	21 000
Continental bakelite	CB	do	do	166	Jan. 18, 1919	19 800
	CB	do	do	166	Feb. 11, 1919	22 400
Bakelite micarta	32–X	Black	do	19	July 25, 1918	17 600
	32–X	do	do	19	Jan. 18, 1919	19 900
	32–X	do	do	19	Apr. 8, 1919	20 300
	32–X	do	do	146	Jan. 7, 1919	19 900
	32–X	do	do	146	Feb. 4, 1919	20 700
	32–X	do	Dull	147	Feb. 11, 1919	21 800
	32–X	do	Polished	25	June 24, 1918	17 100
	323	do	do	150	Feb. 8, 1919	21 400
	323	do	Dull	151	Jan. 8, 1919	19 400
	323	do	do	151	Feb. 7, 1919	21 800
Bakelite micarta (purchased in open market)	Probably 213	Natural	Polished	15	Aug. 13, 1918	18 600
	do	do	do	15	Jan. 17, 1919	19 300
	do	do	do	15	Jan. 18, 1919	20 800
	21–D	do	do	182	Feb. 11, 1919	22 100
Condensite celoron	10	do	do	160	Feb. 17, 1919	21 500
	15	Black	do	186	Jan. 7, 1919	19 100
	15	do	do	186	Feb. 8, 1919	21 100
	10	Natural	do	187	Feb. 11, 1919	21 600
	20	do	do	218	Feb. 14, 1919	27 800
Formica	M	Black	do	5	July 23, 1918	16 300
	M	do	do	5	Jan. 18, 1919	21 500
	M	do	Dull	212	Feb. 5, 1919	20 800
	M	do	do	168	Feb. 5, 1919	20 700
	M	do	Polished	101	Aug. 28, 1918	18 500
	M	do	do	101	Jan. 14, 1919	19 000
	M	do	do	101	Feb. 5, 1919	21 000
	M–2	do	do	50	July 27, 1918	17 200
	M–2	do	do	50	Jan. 8, 1919	21 800
	M–2	do	do	50	Apr. 8, 1919	20 800
	M–2	do	do	116	Feb. 4, 1919	21 000
	M–2	Natural	Dull	140	Feb. 8, 1919	22 300
	P	do	do	103	Aug. 13, 1918	18 400
	R	do	do	172	Feb. 11, 1919	21 000
Hard rubber	Not known	Black	Polished		July 31, 1918	20 600
	do	do	do		Jan. 7, 1919	19 800

4. SURFACE RESISTIVITY

The results of the measurements of surface resistivity on representative samples are shown graphically in the following Figs. Nos. 28 to 39.

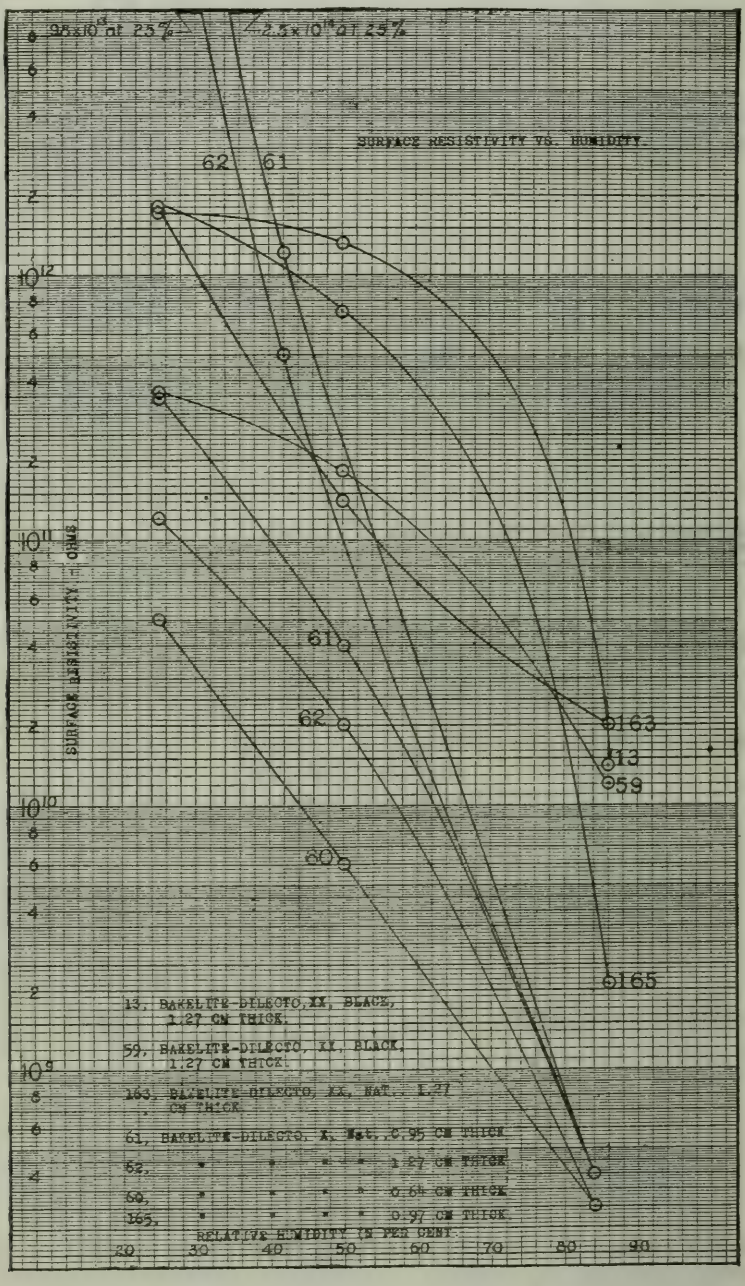

FIG. 28.—*Change of surface resistivity with humidity, of Bakelite-Dilecto, grades XX and X*

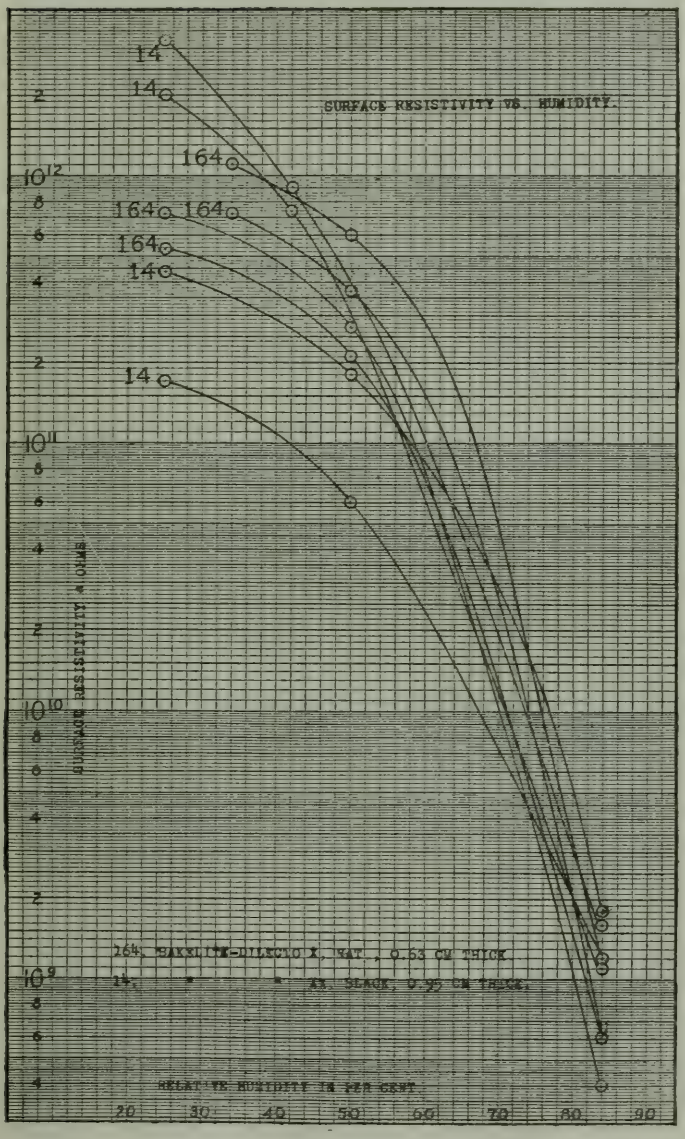

FIG. 29.—*Change of surface resistivity with humidity, of Bakelite-Dilecto, grades X and XX*

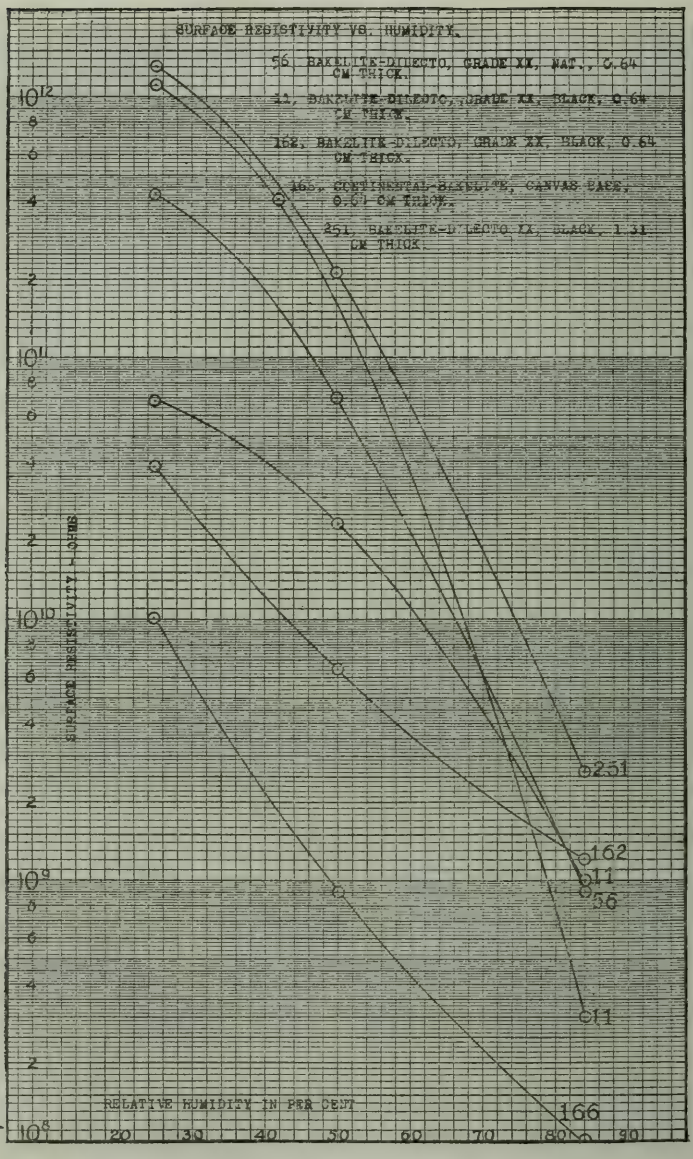

FIG. 30.—*Change of surface resistivity with humidity, of Bakelite-Dilecto, grades XX and CB*

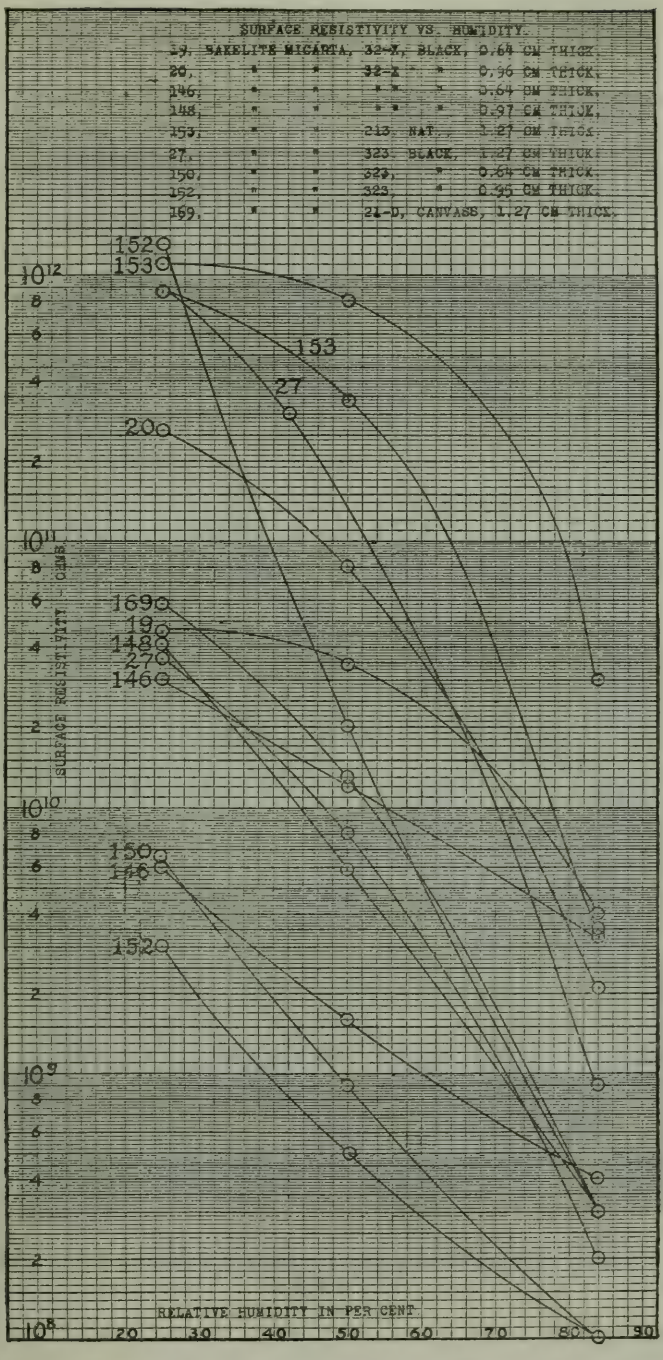

FIG. 31.—*Change of surface resistivity with humidity, of Bakelite Micarta, grades 32-X, 213, 323, and 21-D*

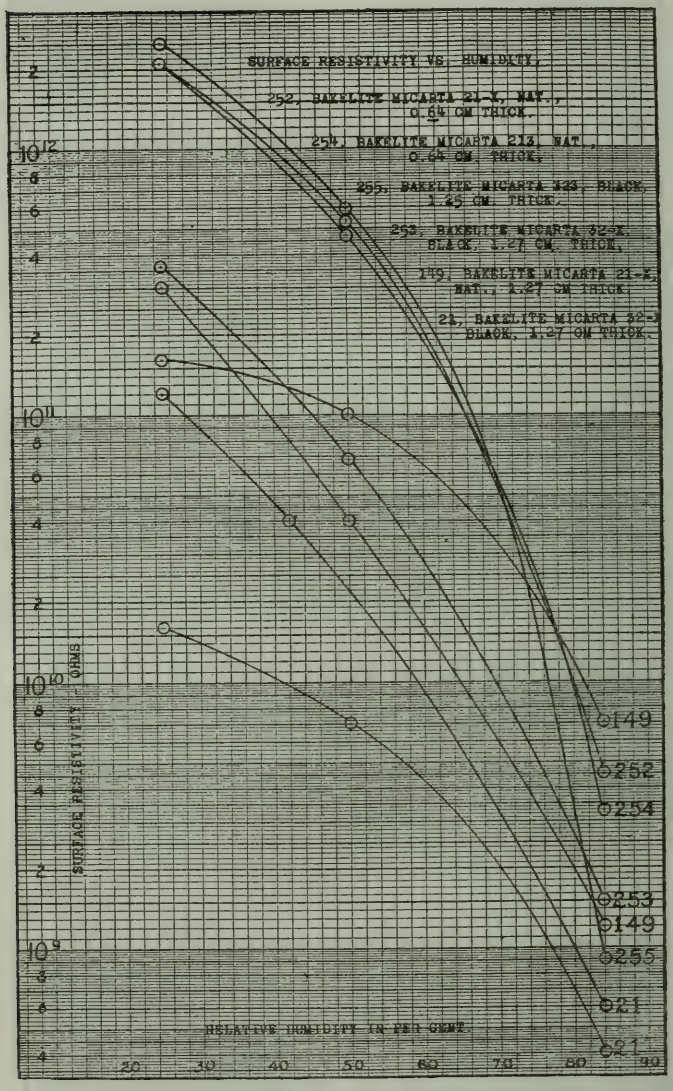

FIG. 32.—*Change of surface resistivity with humidity, of Bakelite Micarta, grades 21-X, 213, and 323*

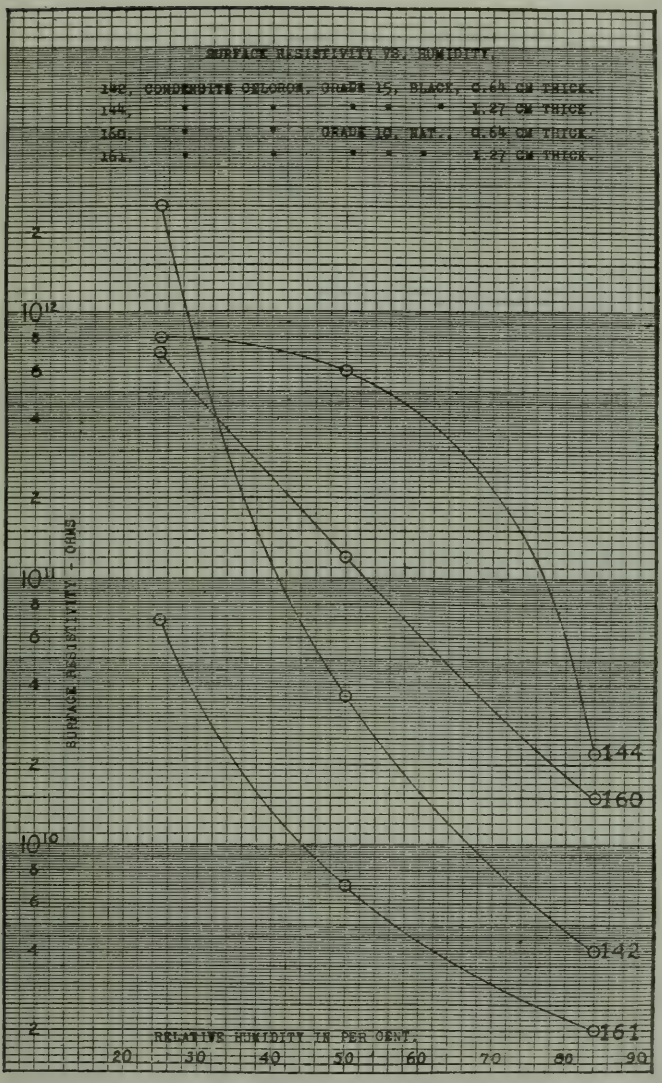

FIG. 33.—*Change of surface resistivity with humidity, of Condensite Celoron, grades 15 and 10*

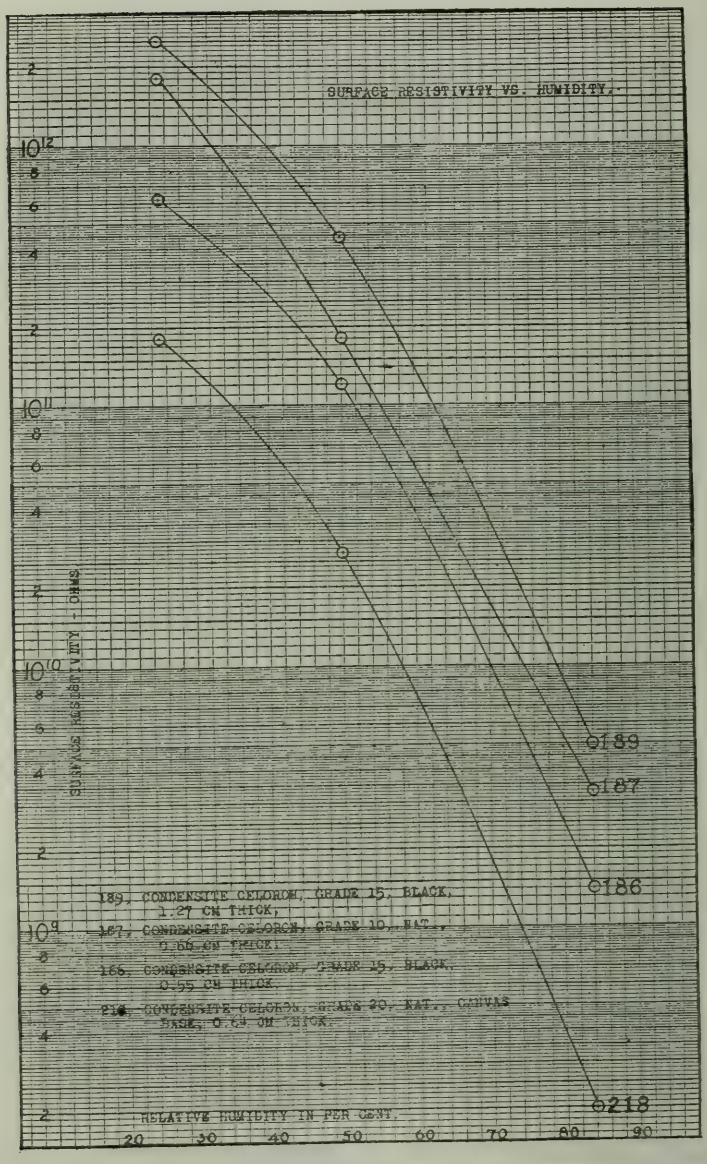

FIG. 34.—*Change of surface resistivity with humidity, of Condensite Celoron, grades 10, 15, and 20*

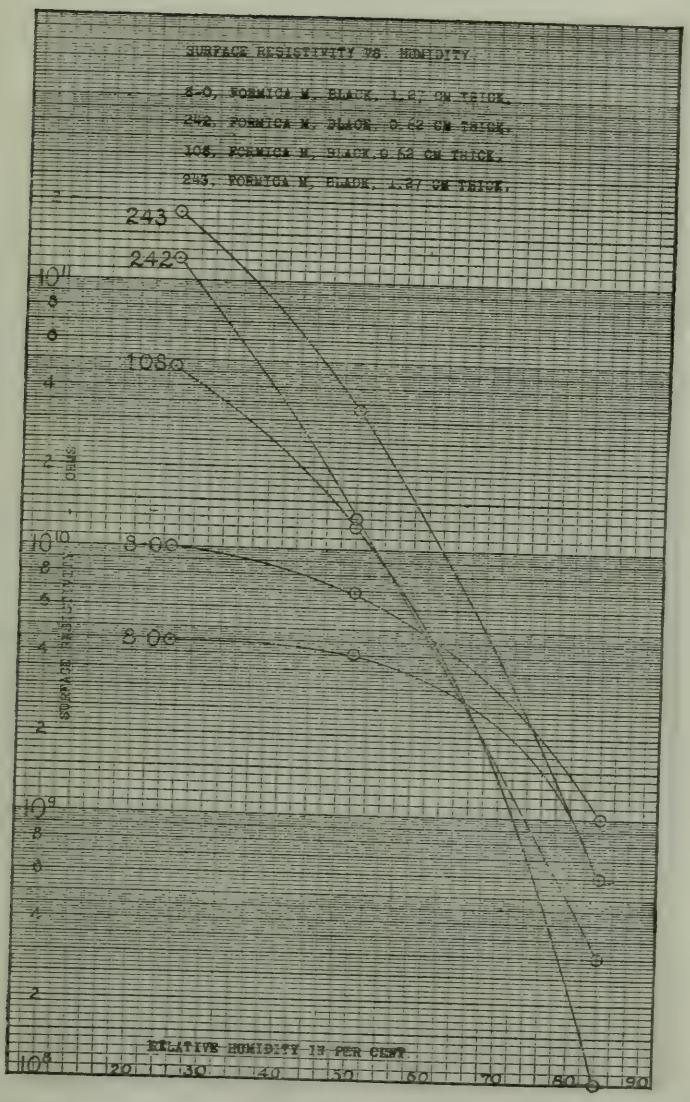

FIG. 35.—*Change of surface resistivity with humidity, of Formica, grade M*

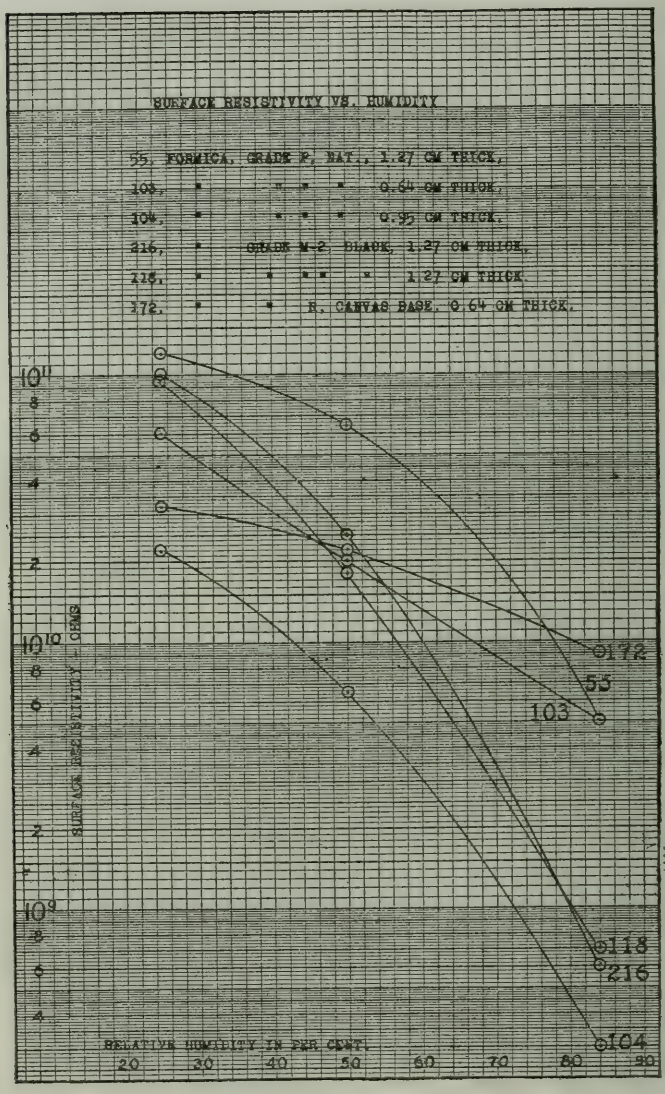

FIG. 36.—*Change of surface resistivity with humidity, of Formica, grades P, M-2, and R*

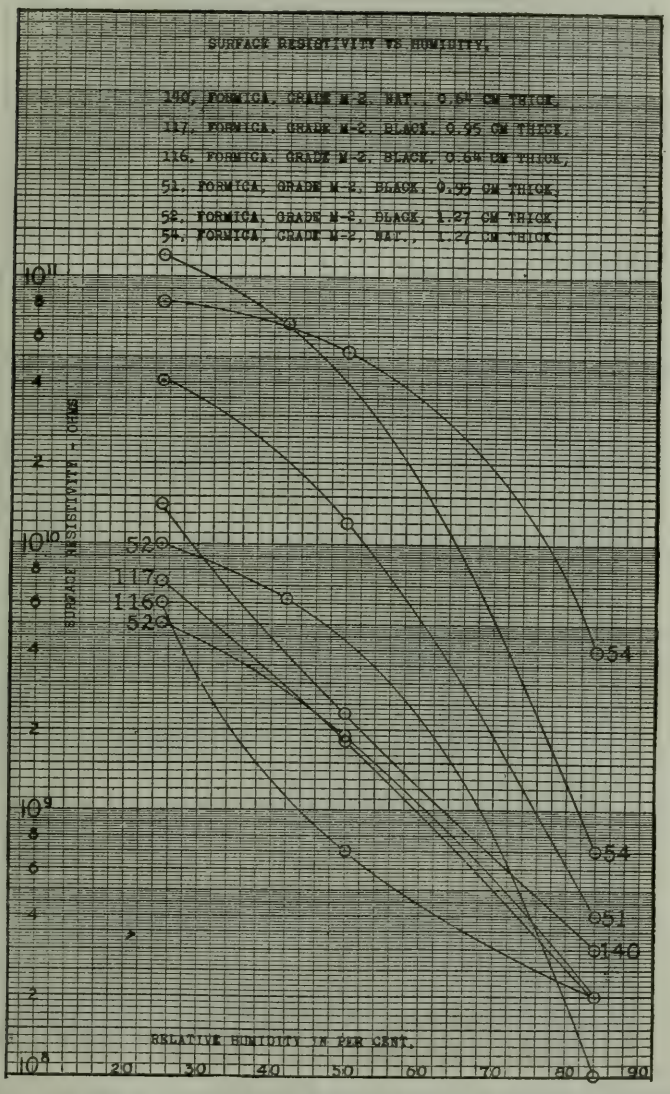

FIG. 37.—*Change of surface resistivity with humidity, of Formica, grade M-2*

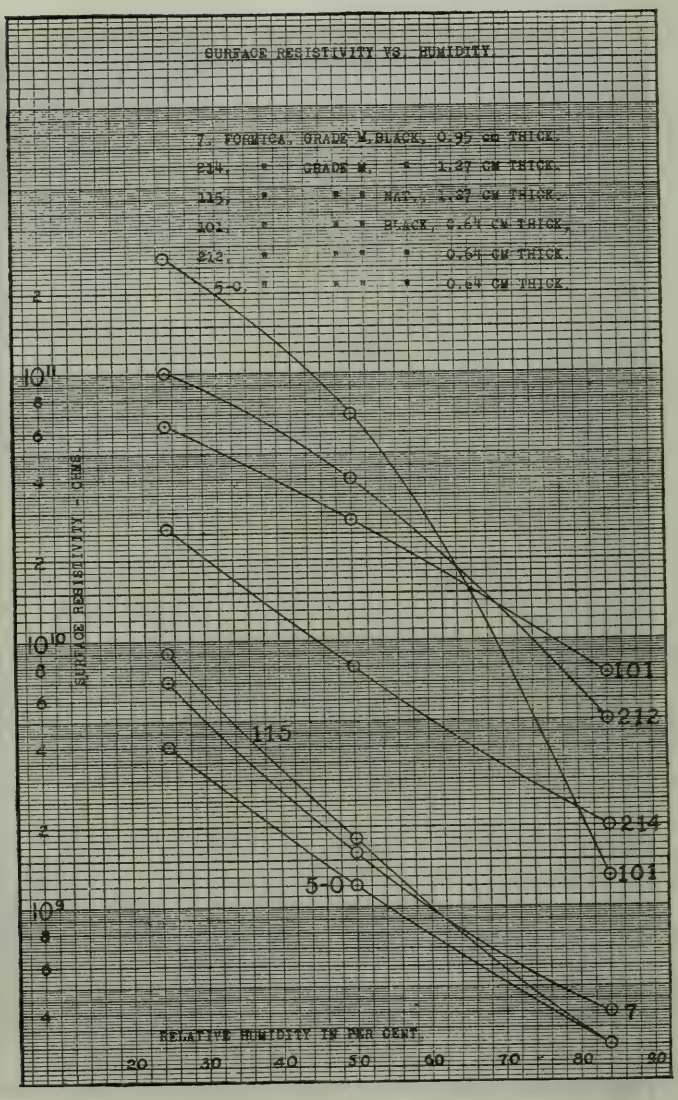

FIG. 38.—*Change of surface resistivity with humidity, of Formica, grade M*

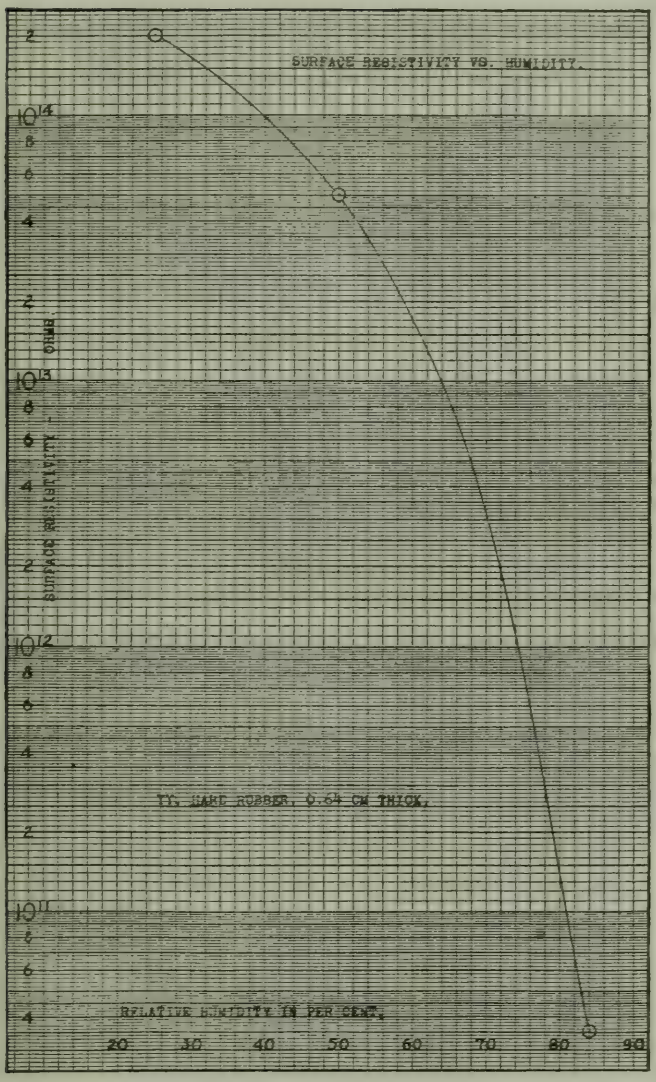

FIG. 39.—*Change of surface resistivity with humidity, of hard rubber, sample taken from stock, grade not known*

5. TENSILE AND TRANSVERSE STRENGTH

The results of the measurements of tensile and transverse strength on representative samples are shown graphically in the following Figs. Nos. 40 to 51.

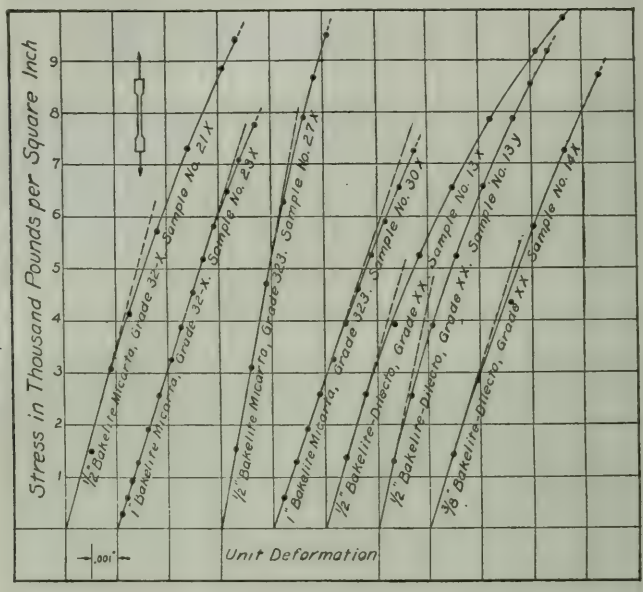

FIG. 40.—*Stress-strain curves, tensile strength tests on Bakelite-Dilecto and Bakelite Micarta, showing the tensile proportional limit*

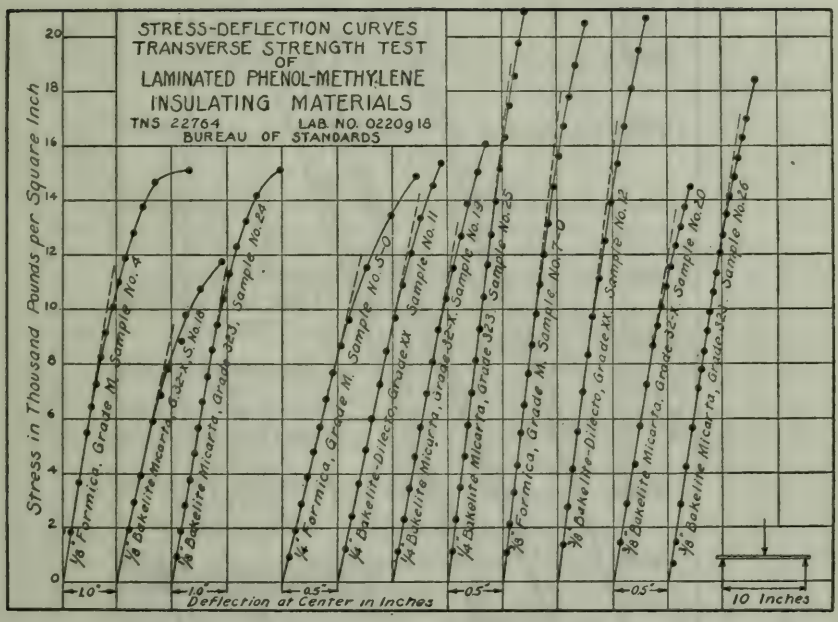

FIG. 41.—*Stress-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, and Formica, showing the transverse brobortional limit*

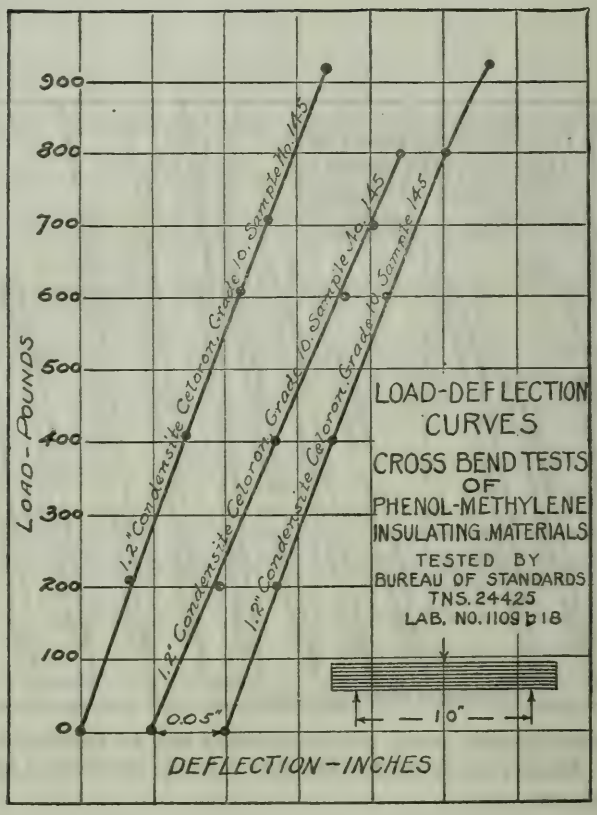

FIG. 42.—*Load-deflection curves, transverse strength tests on Condensite Celoron, grade 10*

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

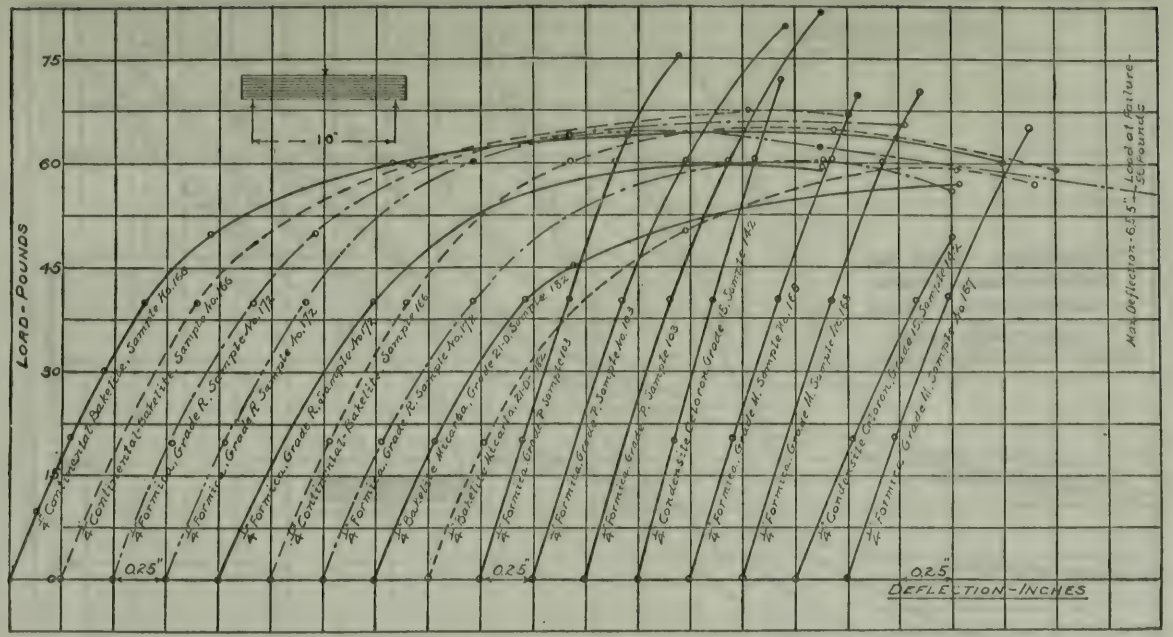

FIG. 43.—*Load-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, Condensite Celoron, and Formica*

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

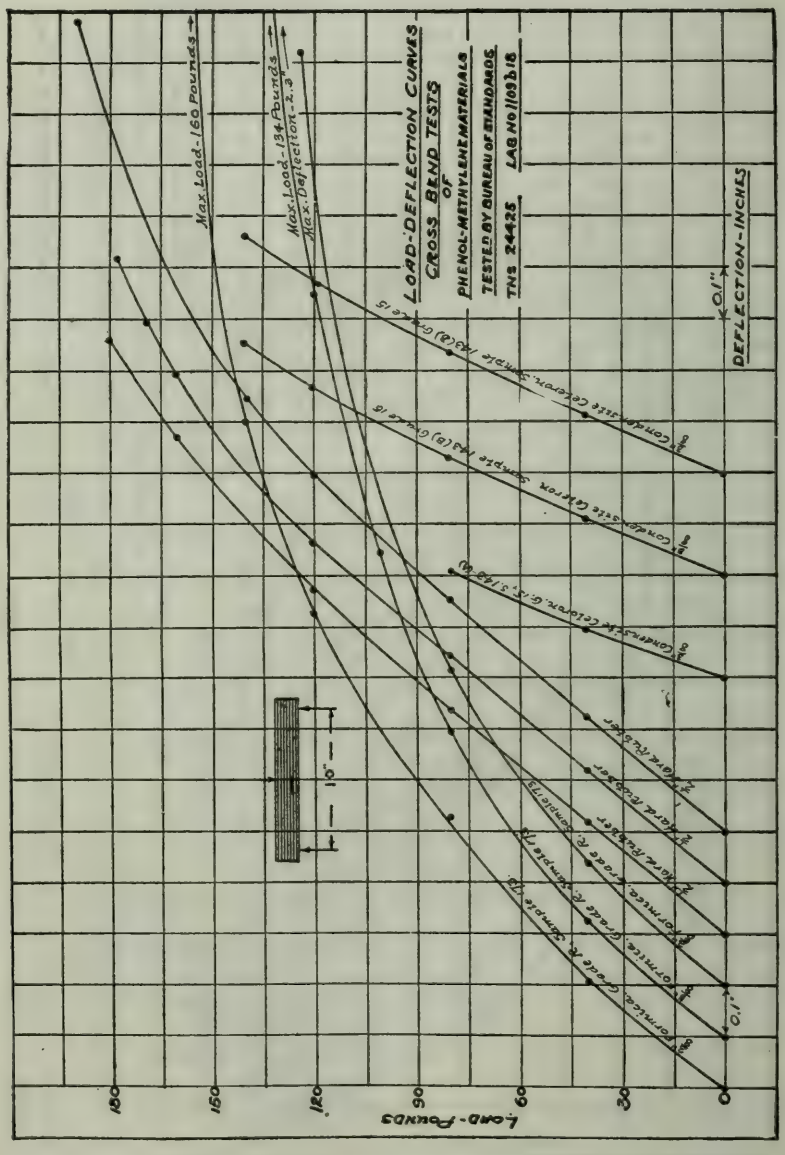

FIG. 44—*Load-deflection curves, transverse strength tests on Condensite Celoron, Formica and hard rubber*

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

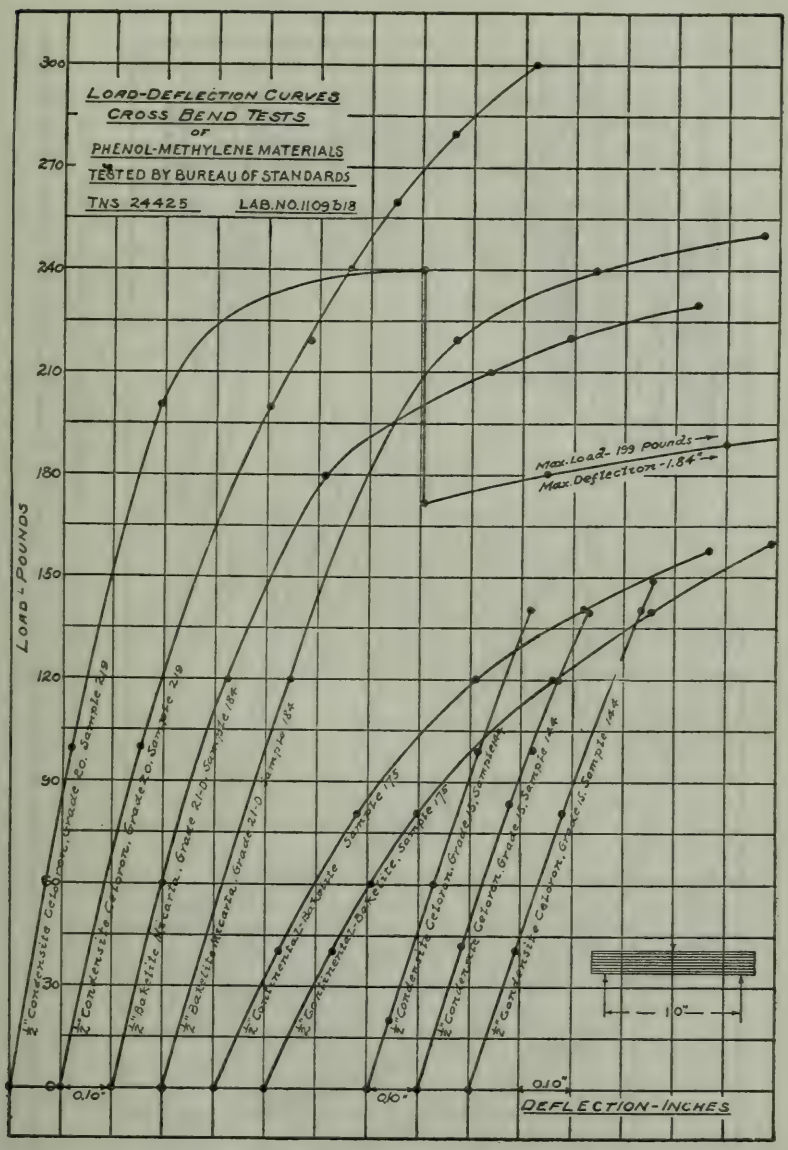

FIG. 45.—*Load-deflection curves, transverse strength tests on Bakelite Micarta, Condensite Celoron, and Continental-Bakelite*

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

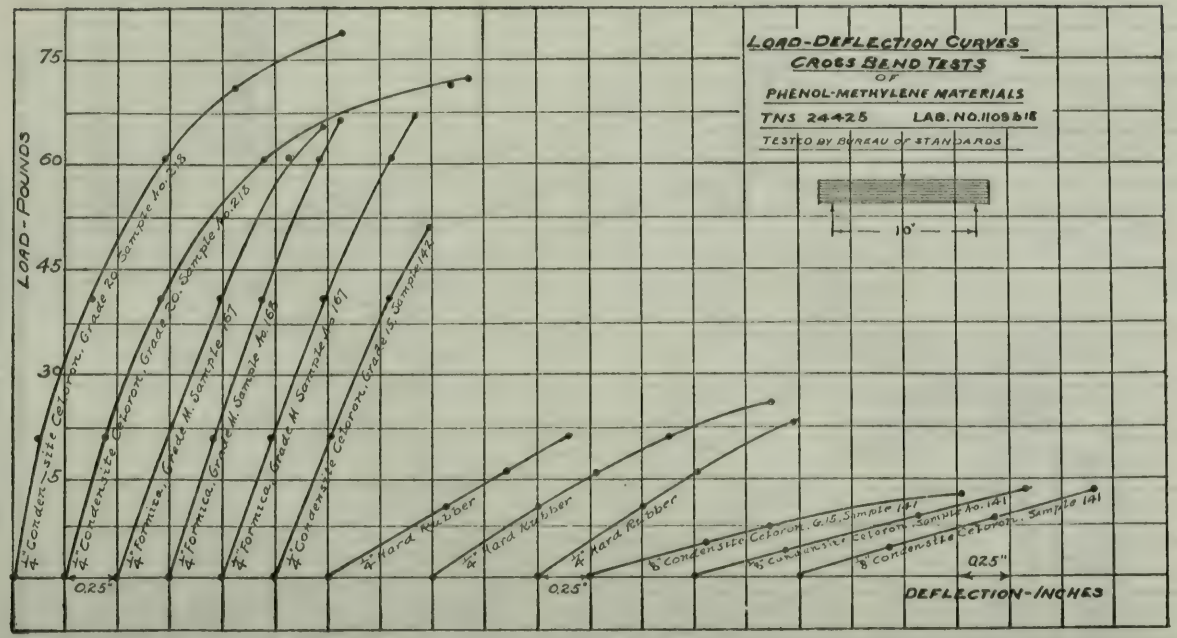

FIG. 46.—*Load-deflection curves, transverse strength tests on Condensite Celoron, Formica and hard rubber*

Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

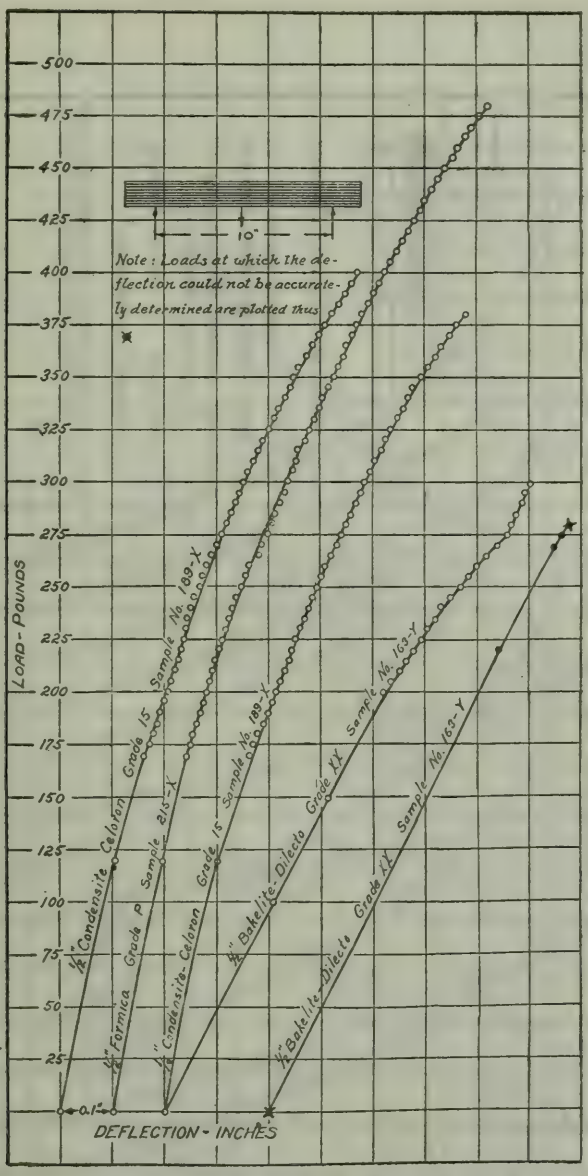

FIG. 47.—*Load-deflection curves, transverse strength tests on Bakelite-Dilecto and Condensite Celoron*

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

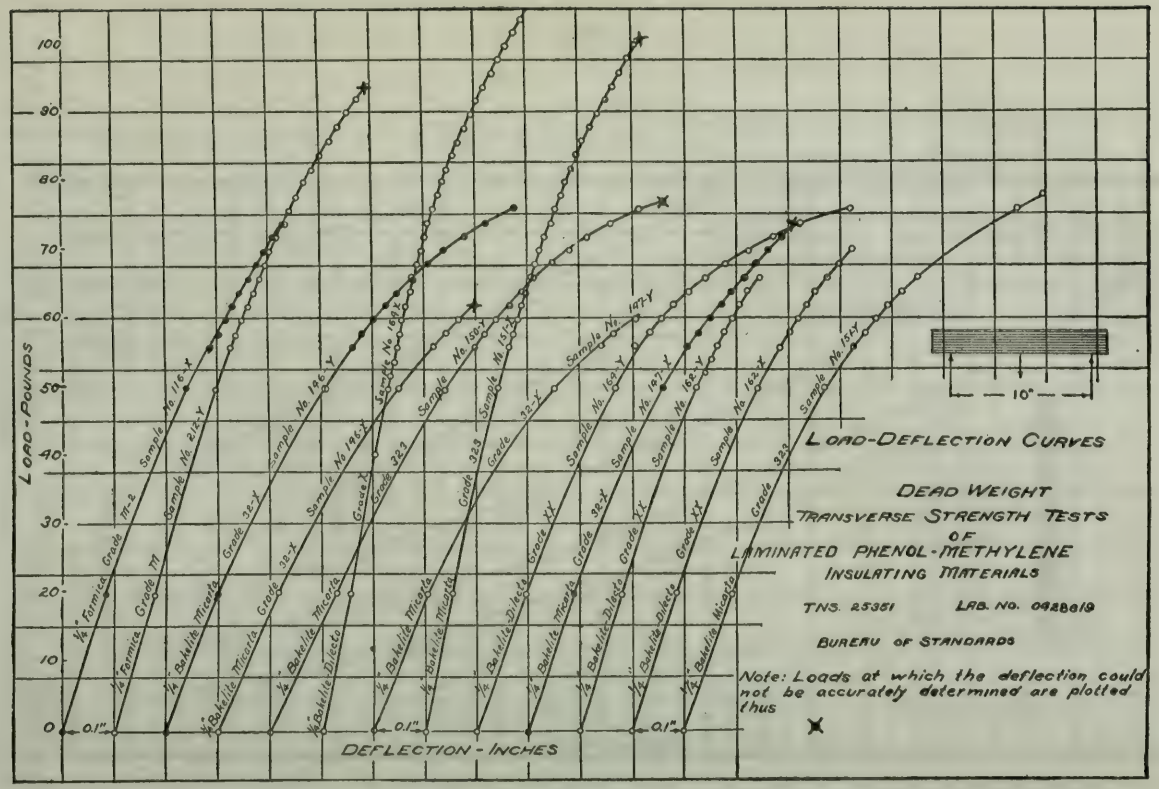

FIG. 48.—*Load-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, and Formica*

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

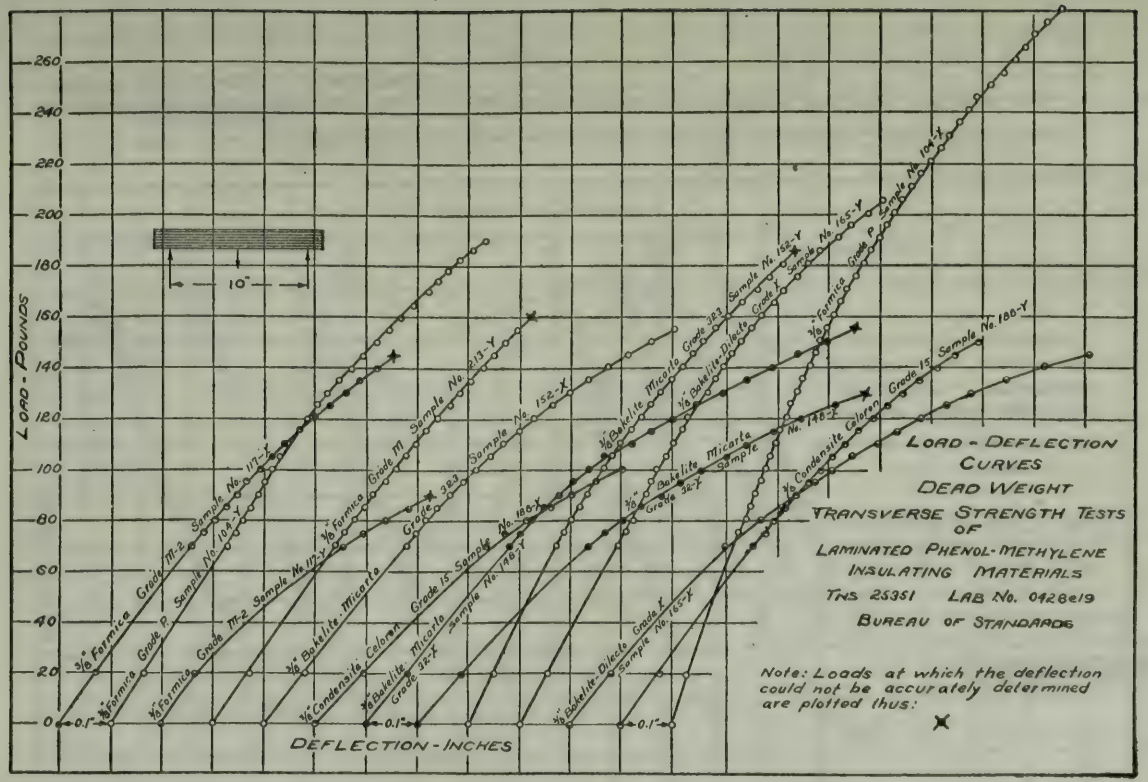

FIG. 49.—*Load-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, Condensite Celoron, and Formica*

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

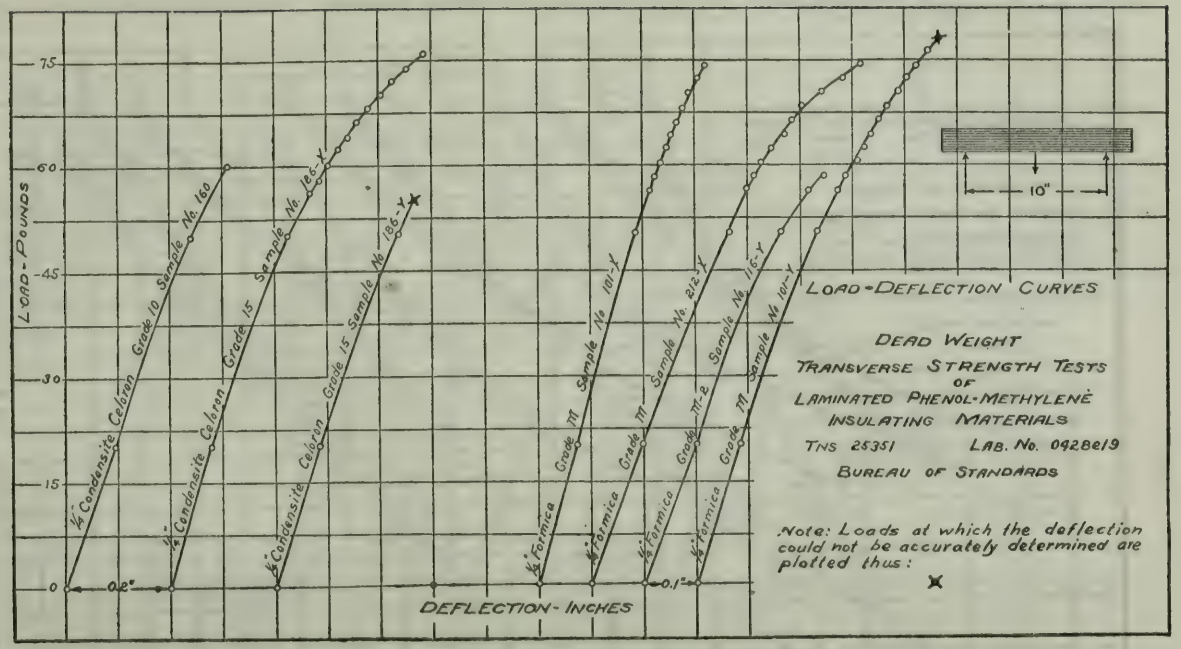

FIG. 50.—*Load-deflection curves, transverse strength tests on Condensite Celoron and Formica*

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

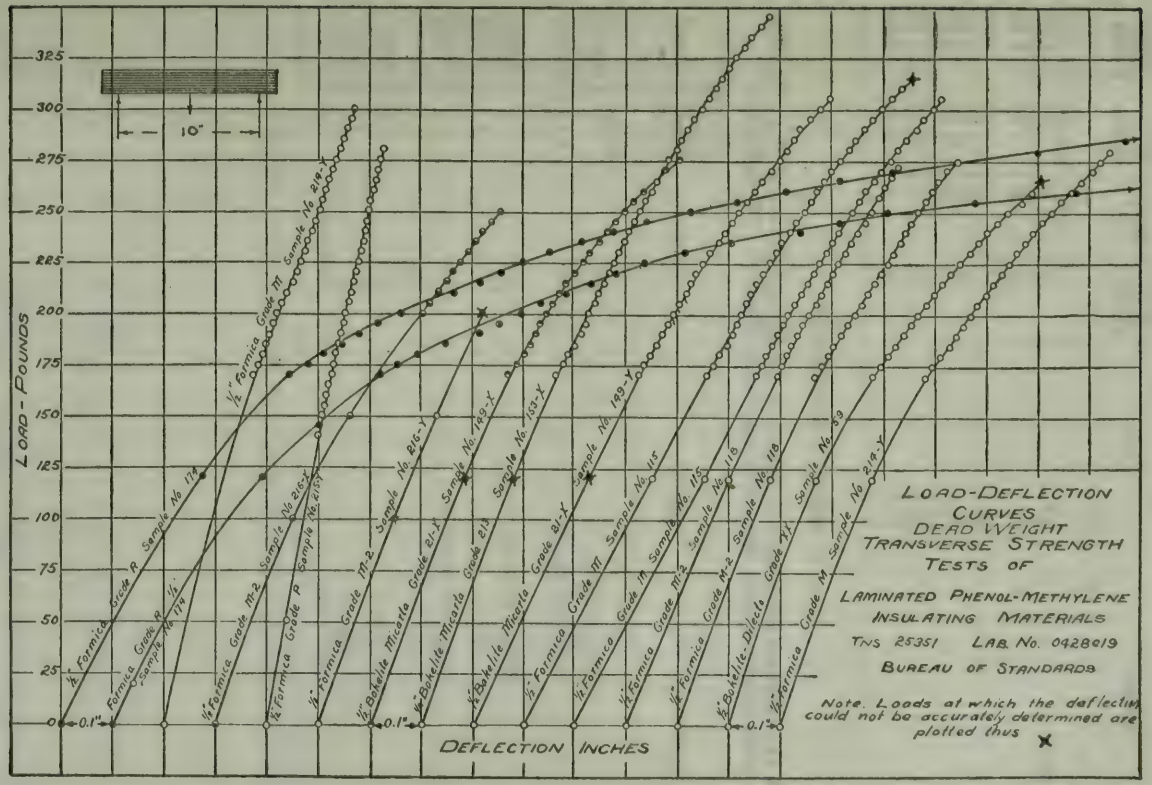

FIG. 51.—*Load-deflection curves, transverse strength tests on Bakelite-Dilecto, Bakelite Micarta, and Formica*

All samples approximately 1 inch wide. Tested in apparatus described in paper mentioned on page 506. For results computed to pounds per square inch of cross section, see pages 524 to 533.

TABLE 10.—Showing the Relation between Transverse and Tensile Proportional Limit Data Gathered from Tests on Bakelite Dilecto and Formica

Material	Grade	B. S. sample number	Thickness	Transverse P-limit	Average tensile P-limit
			Inch	Lbs./in.²	Lbs./in.²
Bakelite-Dilecto	XX	56	0.23	7 200	3 500
	X	61	.37	15 000	4 700
	X	62	.50	6 500	5 300
Formica	M	47	.25	8 500	4 400
	M	48	.24	9 100	4 800
	M	49	.25	12 000	4 900
	M-2	50	.25	9 100	8 000
	M-2	52	.52	14 000	3 600
	M-2	54	.50	13 000	4 300
	P	55	.52	9 400	4 500

6. IMPACT STRENGTH

TABLE 11.—Average Resistance to Impact of the Several Grades of Phenolic Electrical Insulation and Hard Rubber, Using Standard Test Specimens

B. S. sample number	Material	Grade	Average impact strength	Base
			Ft.-lbs.	
59	Bakelite-Dilecto	XX	0.7	Paper.
62	do	X	.9	Do.
175	Continental-Bakelite	CB	[a] 1.5 x 1.0 y	Canvas.
21	Bakelite Micarta	32-X	.2	Paper.
153	do	213	.8	Do.
169	do	21-D	2.1	Canvas.
144	Condensite Celoron	15	.4	Fiber.
161	do	10	.4	Do.
219	do	20	1.0	Canvas.
8-0	Formica	M	.3	Paper.
118	do	M-2	.3	Do.
55	do	P	1.5	Do.
174	do	R	2.9	Canvas.
	Hard rubber	Not known	.1	

[a] x and y are used merely to indicate that specimen x is cut at right angles to specimen y.

7. PERMANENT DISTORTION

TABLE 12.—Summary of Permanent Distortion Data on the Several Grades of Phenolic Electrical Insulating Materials Using Samples 14 Inches Long and Loaded over a Span of 12 Inches

[X following slab number means sample cut one way of grain; Y, cut opposite way of grain]

B. S. sample number	Thickness in inches	Material	Grade	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set
				Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch
162	¼	Bakelite-Dilecto	XX			25	0.063			40	0.157								
162	¼	do	XX	5½	0.008	11	.010	34	0.133	40	.189								
163	½	do	XX									50	0.010					150	0.071
163	½	do	XX									50	.009			100	0.018	150	.046
164	¼	do	X									50	(a)						
164	¼	do	X									51	.007			100	0.114	150	(a)
62	½	do	X									50	.017					150	.056
62	½	do	X									50	.009					150	.037
166	¼	Continental-Bakelite	CB			22	.169			40	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
166	¼	do	CB			25	.139			40	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
175	½	do	CB									50	.003					150	(a)
175	½	do	CB									51	.016			100	.077		
146	¼	Bakelite Micarta	32-X					33	.125	40	(a)								
146	¼	do	32-X	5½	.005			33	.147	40	(a)								
149	½	do	21-X									50	.012			100	.029	150	.094
149	½	do	21-X									51	.010			100	.144		
150	¼	do	323			25	.076			40	.185								
150	¼	do	323	5½	.006	10¾	.012	22½	.049	33	.120								
153	½	do	213									50	.000					150	.138
153	½	do	213									45	.016			100	.025	150	.059
182X	¼	do	21-D	5	.009	22	.146												
182Y	¼	do	21-D	5¾	.016														
184Y	½	do	21-D	15	.005							51	.012					150	.372
184X	½	do	21-D	17½	.005							51	.024					150	(a)
187	¼	Condensite Celoron	10	5¼	.011														

(a) Broke.

(b) Slipped under extreme distortion.

TABLE 12.—Summary of Permanent Distortion Data on the Several Grades of Phenolic Electrical Insulating Materials Using Samples 14 Inches Long and Loaded over a Span of 12 Inches—Continued

[X following slab number means sample cut out one way of grain; Y, cut opposite way of grain.]

B. S. sample number	Thickness in inches	Material	Grade	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set	Load	Set
				Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch
187	1/4	do	10			25	.048			40	(a)					100	.114	150	(a)
144	1/2	do	15									51	.007			100	.015	150	(a)
144	1/2	do	15			25	.000					50	.003						
218Y	5/8	do	20			25	.108			40	.283					100	.022	150	(a)
219X	5/8	do	20																
168	1/4	Formica	M					33	.038										
168	1/4	do	M			25	(a)												
108	1/4	do	M			25	.062			40	.129								
108	1/4	do	M			25	.079			40	.131								
107	1/2	do	M									50	.025					150	.053
107	1/2	do	M	15	.000	25	.000			35	.004	50	.006					150	.043
116	1/4	do	M-2			25	.115			40	.230								
116	1/4	do	M-2			25	.066			40	.233								
103	1/4	do	P					33	.045	40	.074								
103	1/4	do	P			25	.024			40	.080								
104	3/8	do	P							43	.003			78	0.017	100	.020	125	(a)
104	3/8	do	P									50	.006			100	.032	125	(a)
215	1/2	do	P									50	.012					150	.066
215	1/2	do	P									50	.015					150	.066
172	1/4	do	R	11	.044	22	.166												
172	1/4	do	R	5	.012	11½	.040	22½	.169										
174	1/2	do	R									51	.029			100	.102		
174	1/2	do	R									50	.013					150	.461

a Broke.

PERMANENT DISTORTION OF PANELS.—Two irregular permanent distortion tests were made on panels of the phenolic insulating materials. The test was made at room temperature of 23° C, using an Emery dead-weight testing machine. The panel was supported by 2 V-blocks set 22 inches between centers and the load applied through a V-block mounted at the center of the span. Progressive load increments of 50 pounds were used, and all load was removed after the application of each 50 pounds increment in order to note the permanent set that was developed during loading. At intervals during loading the load was allowed to stand for 24 hours and then was removed so as to determine whether any increase in permanent set had occurred. One sample panel measured 18 by 24 inches by ½ inch thick.

Up to a load of 597.5 pounds this panel seemed perfectly elastic. This load caused a deflection of 0.5 inch and was allowed to remain on for 24 hours, after which time the load was removed and it was found that a permanent set of 0.0938 inch had developed. The load was then reapplied to a total of 797.5 pounds, at which load the deflection was 0.8 inch. This load was also allowed to remain on the panel for a 24-hour period. On removal of the load it was found that the permanent set had increased to 0.1563 inch.

The second sample measured 18 by 24 inches by ⅜ inch thick. The above method was followed in this test except in regard to time of loading and the number of Ames dials used. Deflections are measured by means of two Ames dials set at either end of the center V-block. Up to a load of 397 pounds the panel seemed perfectly elastic. This load was allowed to remain on the panel for a 44-hour period, and upon removal of the load it was found that a permanent set of 0.25 inch had developed. The results of this test are given below in tabulated form.

TABLE 13.—Temporary and Permanent Distortion Data Taken on One Sheet of Phenolic Electrical Insulating Material, 18 by 24 by ⅜ inch. The Method is Described Above

Load (pounds)	Dial No. 1	Dial No. 2	Load (pounds)	Dial No. 1	Dial No. 2
Increasing loads:	Inch	Inch	Decreasing loads after 44-hour applied load:	Inch	Inch
Pan[a]	0.00380	0.00387	Pan+300	0.00909	0.00950
Pan+50	.00459	.00484	Pan+250	.00901	.00950
Pan+100	.00531	.00562	Pan+200	.00850	.00907
Pan+150	.00604	.00703	Pan+150	.00778	.00832
Pan+200	.00685	.00799	Pan+100	.00696	.00730
Pan+250	.00800	.00869	Pan+50	.00612	.00635
Pan+300	.00871	.00935	Pan	.00528	.00540

[a] Weight of pan approximately 97 pounds.

NATURAL DISTORTION OR WARP.—Some difficulty has been experienced by the various apparatus manufacturers using the laminated phenolic materials with sheets of the insulating material having a large natural warp. This property of the various materials has not been systematically considered in this investigation. Judging from the samples we have received, all the laminated phenolic materials are liable to have a certain amount of natural warp. Whether this warping increases with time we are not able to state, for no measurements have been made.

One sample which seemed to be warped the worst was selected from each kind of material and the maximum sag measured. The sag was measured by placing a rigid meter bar diagonally across the sheet and observing the distance the sheet sagged from the center of the straight bar 1 meter long.

TABLE 14.—Observations on the Natural Warp of Four Standard Sheets of Phenolic Electrical Insulating Material

Material	Grade	Approximate thickness		Average sag
		cm	Inch	cm
Continental-Bakelite	CB	0.64	¼	1.1
Bakelite Micarta	32–X	.95	⅜	2.1
Condensite Celoron	15	.64	¼	.4
Formica	M	.95	⅜	.7

8. MACHINING QUALITIES

A description of the method of determining the machining qualities of the laminated phenolic materials is given in the Bureau publication mentioned on page 506. A discussion of the results follows this discussion on pages 505 to 507. Both of these references are needed for an understanding of the following tabulated results:

TABLE 15.—Results of Sawing Tests (Test No. 1)

[Used 12-inch hollow-ground circular saw; no set; speed, 1830 revolutions per minute; cutting teeth per second, 6780; speed of travel, 5750 feet per minute]

Material	Grade	Saws		Phenol odor	
		Fairly easily	Easily	Faint	Strong
Bakelite-Dilecto	XX	x		x	
	X		x	x	
Continental-Bakelite	CB	x		x	
Bakelite Micarta	32-X	x			x
	323	x			x
	21-D		x	x	
Condensite Celoron	15	x			x
	20		x		x
Formica	M		x	x	
	M-2	x		x	
	P		x	x	
	R	x			x

Notes on tests Nos. 2 to 9, inclusive, Table 16. Test numbers refer to the method as outlined in the Bureau publication mentioned on page 506; b–1, b–2, and b–3 refer to the questions stated in the same paper. L and R refer to the machinists making the tests, Messrs. Lund and Rheinbold.

Column 5 is given because in some cases it was very hard to choose one material which was best in respect to questions b–1 and b–2. As an example, operator L decided that in test No. 2 Grades XX, 323, 15, and M–2 worked very similarly to 32–X, X, and P, but dulled the lathe tool a little more rapidly.

GRADES.—Only the grade numbers of material are put in the data table. This is done for compactness. The meaning of XX, X, CB, etc., are given on pages 508 and 509. The names of the companies manufacturing these grades are given on pages 508 and 509.

MEANING AND ORDER OF ENTRIES IN TABLE.—The grades given in the table below are those which showed noticeable superiority in the particular quality and kind of test indicated. Thus, under column 2 and test No. 2, the grades 32–X and R appear. This means that 32–X and R exhibited superior ease of machining in test No. 2. The entries in column 4 are the grades which had least effect on the machine tool. In all cases where more than one grade appears in the same group the order of arrangement is the arbitrary alphabetical arrangement used elsewhere in this paper and indicates no preference. That is, the order is X, P, for instance, because those letters represent Bakelite-Dilecto, grade X, and Formica, grade P.

TABLE 16.—Materials Which Showed Superiority in the Various Machining Tests

1	2		3		4		5	6
Test number and description	Ease of machining b–1		Quantity of machined surface b–2		Effect on machine tool b–3		Similarity in general working to the better materials under b–1 and b–2	Notes
	L	R	L	R	L	R		
2, lathe turning, to determine quality of machined surface	32–X.. R.....	CB....	X..... R..... M....	CB.... X..... 32–X..	32–X.. R.....	X..... CB.... 32X.... 323.... 21–D.. M.... P..... R.....	XX..... 323..... 15..... M–2.....	
3, lathe turning, to determine effect on tool	32–X.. 21–D..	X.....	X.....	X..... CB.... 21–D.. R.....	32–X..	X..... CB.... 21–D.. R.....	XX..... 323..... M..... M–2.....	
4, ability to take a die-cut thread, ¼ inch, 20-thread	XX....	XX....	M–2...	XX.... M.....	XX.... M–2..	XX....	32–X.... 323..... 15..... M.....	All samples difficult to die thread
5, ability to take a machine thread, ¼ inch, 20-thread	323.... M.....	.....	CB.... 32–X..	XX.... CB.... 32–X.. M.....	.....	.....	.....	
6, drilling, nature of hole and effect on drill	XX.... 32–X..	R..... (a)	XX.... 32–X.. M–2...	XX.... 32–X.. 15..... M..... M–2...	20.....	R.....	X..... CB..... 21–D.... 20..... P.....	
7, screw thread tapping, ¼ inch, 20-thread	R.....	.....	XX....	(b)	R.....	.....	(b)	
8, splitting, drilling and tapping parallel to laminations	(b)	XX.... 323.... M–2... 20.....	323....	.....	(b)	.....	(b)	X, P, and 15 split
9, planing, to determine degree of splitting	20.....	CB....	CB....	CB.... 21–D.. R.....	20.....	(b)	(b)	

[a] Others about equal. [b] All about equal.

9. THERMAL EXPANSIVITY

An extended study was made of these materials with a view to determining their applicability for use in instruments of high precision which may be subjected to temperature variations.

The accompanying representative curves (Figs. 52 and 53) are self-explanatory and in general show the tendency of contraction at constant temperature (above 60° C) of any of the materials dealt with in this paper. Similar curves are given for many other samples of laminated phenolic materials in Bureau of Standards Scientific Paper No. 352, "Thermal Expansion of Insulating Materials," by Wilmer H. Souder and Peter Hidnert. In most

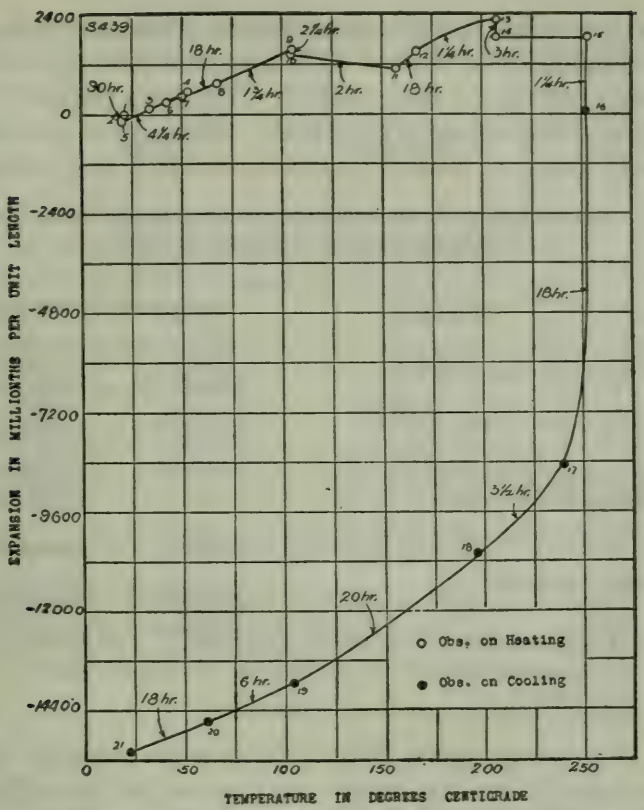

FIG. 52.—*Expansion of Bakelite-Dilecto, grade XX*

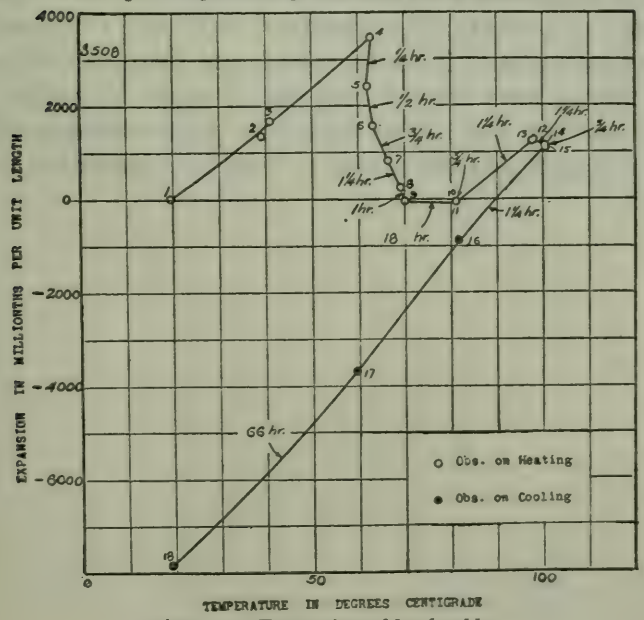

FIG. 53.—*Expansion of hard rubber*

cases, after cooling to room temperature, these materials show a marked diminution in length. The numbers near the circles represent the order of the observations. The time elapsing between consecutive observations is indicated. When the time is less than one hour (except at critical temperatures) it is not indicated.

TABLE 17.—Summary of the Coefficients of Expansion Obtained on Various Samples of Phenolic Electrical Insulating Material

B. S. number	Material	Sample heated in—	Average coefficients $\times 10^6$
S446	Bakelite-Dilecto (black, XX grade)	Air furnace	22 between 20 and 60° C
S447	do	Oil bath	36 between 30 and 100° C
S448	Bakelite-Dilecto (natural, XX grade)	Air furnace	26 between 25 and 60° C
S449	do	Oil bath	28 between 30 and 100° C
S439	Bakelite-Dilecto (XX grade)	Air furnace	21 between 25 and 50° C
S440	Bakelite Micarta (32–X grade)	do	33 between 25 and 50° C
S441	Bakelite Micarta (323 grade)	do	29 between 25 and 50° C
S451	Continental-Bakelite (CB grade)	do	(a)
S450	do	Oil bath	31 between 25 and 60° C
S432	Formica (grade M) [b]	do	33 between 20 and 60° C
S433	do.[b]	Air furnace	30 between 20 and 60° C
S434	do.[b]	Oil bath	20 between 20 and 60° C
S435	do.[b]	Air furnace	14 between 20 and 60° C
S508	Hard rubber (rod)	do	80 between 20 and 60° C

[a] Expansion very irregular.
[b] Nos. S432 and S433 were cut perpendicular to Nos. S434 and S435.

Most of these materials when kept at some constant temperature above 60° C shrink in length and lose weight (give off vapors). When the temperature of the material increases, it expands; but when kept at a constant temperature above 60° C it contracts.

The following table gives the maximum temperatures to which the specimens were heated and the changes in weight and in length after the test. The plus (+) sign indicates a gain in weight or length and the minus (−) sign a diminution in weight or length.

TABLE 18.—Showing the Percentage of Change in Weight and Length of 14 Samples of Phenolic Electrical Insulating Material When Surrounded with Heated Air or Oil

B. S. number	Material	Sample heated in—	Maximum temperature	Change in weight after test	Change in length after test
			° C	Per cent	Per cent
S446	Bakelite-Dilecto (black, XX grade)	Air furnace	172	−6.3	−0.4
S447	do	Oil bath	147	−0.1	−0.2
S448	Bakelite-Dilecto (natural, XX grade)	Air furnace	191	−2.8	−0.2
S449	do	Oil bath	175	−0.3	−0.2
S439	Bakelite-Dilecto (XX grade) [a]	Air furnace	253	−20.4	−1.5
S440	Bakelite Micarta (32–X grade)	do	195	−2.7	−0.4
S441	Bakelite Micarta (323 grade) [a]	do	246	−27.6	−4.0
S451	Continental-Bakelite (CB grade)	do	170	−2.0	−0.1
S450	do	Oil bath	160	+0.1	−0.2
S432	Formica (grade M)	do	60	+0.2	−0.01
S433	do	Air furnace	79	−0.6	−0.14
S434	do	Oil bath	61	+0.2	0.00
S435	do	Air furnace	66	−0.3	−0.03
S508	Hard rubber	do	100	−0.1	−0.8

[a] After test, specimen was found warped, cracked on sides, and blistered on upper and lower surfaces.

From a study of the work on these materials it is evident that the length is a function of the temperature, medium in which the material is heated (air or oil), time, rapidity of heating or cooling, etc.

10. EFFECTS OF CHEMICALS

TABLE 19.—Change in Weight and Surface Hardness Owing to Submerging Phenolic Electrical Insulating Material in a 22 Per Cent (by Weight) Solution of Sulphuric Acid for 48 Hours

B. S. sample number	Material	Grade	Weight in air before submerging in solution	Weight in air after 24 hours out of solution	Change in weight	Weight in air after 48 hours out of solution	Change in weight	Final change in weight	Surface hardness (Brinell, pressure, 500 kg)	
									Before immersion	After immersion
			Grams	Grams	Grams	Grams	Grams	Per cent		
59	Bakelite-Dilecto	XX	84.212	84.319	0.107	84.321	0.109	0.129	41.0	36.0
251	do	XX	85.835	85.964	.129	85.964	.129	.146	37.0	37.0
163	do	XX	84.504	84.607	.103	84.614	.110	.130	39.0	38.0
62	do	X	83.536	84.334	.798	84.326	.790	.947	24.9	18.6
175	Continental-Bakelite	CB	78.336	79.670	1.334	79.669	1.333	1.700	30.4	31.2
21	Bakelite Micarta	32-X	87.577	87.700	.123	87.700	.123	.1405	38.0	38.0
253	do	32-X	84.376	84.481	.105	84.481	.105	.1240	37.0	37.0
149	do	21-X	82.982	83.108	.126	83.109	.127	.1530	34.5	34.5
27	do	323	87.950	88.403	.453	88.389	.439	.5000	37.0	19.3
255	do	323	83.752	84.006	.254	83.998	.246	.2940	37.0	32.6
153	do	213	85.420	85.649	.229	85.647	.227	.2660	37.0	34.5
184	do	21-D	90.698	91.129	.431	91.122	.424	.4670	32.6	33.6
189	Condensite Celoron	15	86.611	88.839	.228	88.839	.228	.257	38.0	36.0
144	do	15	89.250	89.379	.129	89.379	.129	.144	34.5	35.0
219	do	10	106.235	106.954	.719	106.942	.707	.666	30.4	28.4
161	do	10	97.570	97.724	.154	97.723	.153	.157	32.6	32.6
8-0	Formica	M	88.812	88.955	.143	88.957	.145	.163	38.0	36.0
214	do	M	85.520	85.638	.118	85.639	.119	.139	40.0	36.0
107	do	M	83.434	83.524	.090	83.526	.092	.110	45.0	40.0
115	do	M	85.354	85.475	.121	85.477	.123	.144	36.0	35.0
243	do	M	83.728	83.820	.092	83.822	.094	.112	48.0	46.0
216	do	M-2	83.105	83.279	.174	83.279	.174	.210	37.0	34.5
118	do	M-2	84.169	84.221	.052	84.222	.053	.063	49.0	49.0
54	do	M-2	86.202	86.279	.077	86.279	.077	.089	46.0	46.0
52	do	M-2	87.904	88.035	.131	88.038	.134	.152	44.0	43.0
215	do	P	88.759	89.286	.527	89.273	.514	.580	37.0	22.3
55	do	P	90.990	91.587	.597	91.575	.585	.644	38.0	29.1
174	do	R	86.722	87.066	.344	87.053	.331	.382	35.0	35.0

TABLE 20.—Change in Weight and Surface Hardness Owing to Submerging Phenolic Electrical Insulating Material in a 17 Per cent (by Weight) Solution of Sodium Hydroxide for 48 Hours

B. S. sample number	Material	Grade	Weight in air before submerging in solution	Weight in air after 24 hours out of solution	Change in weight	Weight in air after 48 hours out of solution	Change in weight	Final change in weight	Surface hardness	
									Before immersion (Brinell, 500 kg pressure)	After immersion (Brinell, 250 kg pressure)
			Grams	Grams	Grams	Grams	Grams	Per cent		
59	Bakelite-Dilecto	XX	84.661	87.880	3.219	87.438	2.777	3.28	40.0	20.00
251	do	XX	85.184	87.824	2.640	87.746	2.562	3.00	36.0	18.00
163	do	XX	83.234	85.046	1.812	84.951	1.717	2.06	41.0	20.50
62	do	X	83.573	91.230	7.757	90.273	6.700	8.02	28.5	14.25
175	Continental-Bakelite	CB	78.928	87.814	8.986	82.887	3.959	5.01	30.1	15.05
21	Bakelite Micarta	32–X	87.052	90.561	3.509	90.443	3.391	3.89	38.0	19.50
253	do	32–X	82.821	87.247	5.426	87.130	4.309	5.20	34.5	17.25
149	do	21–X	85.460	88.751	3.291	88.668	3.208	3.75	38.0	19.00
27	do	323	87.573	96.151	8.578	95.098	7.525	8.60	37.0	18.00
255	do	323	83.802	91.948	8.146	90.633	6.831	8.13	36.0	18.00
153	do	213	85.225	88.770	3.545	88.661	3.436	4.03	37.0	18.00
184	do	21–D	89.396	93.354	3.958	93.365	3.969	4.71	29.1	14.55
144	Condensite Celoron	15	90.397	93.087	2.690	92.641	2.244	2.48	37.0	18.5
189	do	15	89.660	93.110	3.450	92.769	3.109	3.56	36.0	18.0
219	do	10	106.088	107.543	1.455	107.467	1.379	1.29	29.1	14.5
161	do	10	95.873	98.869	2.996	98.755	2.882	3.01	28.4	14.2
8–0	Formica	M	88.669	92.583	3.914	92.112	3.443	3.88	37.0	18.5
214	do	M	84.015	88.079	4.064	87.819	3.804	4.53	45.0	22.5
107	do	M	83.870	85.789	1.919	85.768	1.898	2.26	45.0	22.5
115	do	M	82.906	87.955	5.049	87.161	4.255	5.13	37.0	18.5
243	do	M	84.080	87.084	3.004	87.534	3.454	4.07	48.0	24.0
216	do	M–2	83.080	89.112	6.032	88.136	5.056	6.04	38.0	19.0
118	do	M–2	84.043	90.206	6.163	89.529	5.486	6.51	49.0	24.5
54	do	M–2	85.953	89.470	3.517	89.163	3.210	3.74	46.0	23.0
52	do	M–2	87.870	91.436	3.560	91.076	3.206	3.65	27.2	13.6
215	do	P	88.815	94.076	5.261	93.808	4.993	5.51	37.0	18.5
55	do	P	90.611	96.067	5.456	95.472	4.861	5.36	38.0	19.0
174	do	R	86.522	89.941	3.419	89.742	3.220	3.72	36.6	13.3

11. SUMMARIES OF PROPERTIES

The following summaries are obtained as averages of the data on the various properties of the laminated phenolic materials as given in section IV–1. This separates the various properties recorded on pages 524 to 533 and shows the average of data on each property as determined at the Bureau of Standards. Since the properties of most of the laminated phenolic materials vary from sample to sample, the average value would be more practical for general use. In some of the data tables a column of per cent variation appears. These values are obtained by computing the average per cent variation from the average.

TABLE 21.—Average Values of Volume Resistivity of 15 Grades of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Volume resistivity
		Inch	cm	ohm-cm×10^3
Bakelite-Dilecto	XX	1/4	0.64	18 000
		3/8	.95	12 000
		1/2	1.27	26 000
	X	1/4	.64	130 000
		3/8	.95	790 000
		1/2	1.27	640 000
Continental-Bakelite	CB	1/4	.64	200
Bakelite Micarta	32–X and 21–X	1/4	.64	12 000
		3/8	.95	15 000
		1/2	1.27	990
	323 and 213	1/4	.64	48 000
		3/8	.95	530
		1/2	1.27	41 000
	21–D	1/2	1.27	100
Condensite Celoron	10 and 15	1/4	.64	4 400
		1/2	1.27	26 000
	20	1/4	.64	63
Formica	M	1/4	.64	5 060
		3/8	.95	270
		1/2	1.27	1 300
	M–2	1/4	.64	25
		3/8	.95	20
		1/2	1.27	710
	P	1/4	.64	90
		3/8	.95	500
		1/2	1.27	2 000
	R	1/4	.64	60

TABLE 22.—Average Values of Surface Resistivity at three Humidities of 15 Grades of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Surface resistivity at relative humidity of—		
				24 per cent	50 per cent	84 per cent
		Inch.	cm	Ohms $\times 10^8$	Ohms $\times 10^8$	Ohms $\times 10^8$
Bakelite-Dilecto	XX	1/4	0.64	89 000	2400	8
		3/8	.95	14 600	4700	14
		1/2	1.27	13 000	4600	120
	X	1/4	.64	4 300	2900	6
		3/8	.95	840 000	6600	[illegible]
		1/2	1.27	490 000	2600	4
Continental-Bakelite	CB	1/4	.64	100	9	1
Bakelite Micarta	32-X and 21-X	1/4	.64	7 100	1900	37
		3/8	.95	1 000	300	9
		1/2	1.27	1 900	520	21
	323 and 213	1/4	.64	14 000	4000	16
		3/8	.95	6 500	100	2
		1/2	1.27	11 000	4100	71
	21-D	1/2	1.27	580	130	3
Condensite Celoron	10 and 15	1/4	.64	14 000	1100	59
		1/2	1.27	11 000	3500	96
	20	1/4	.64	1 800	280	13
Formica	M	1/4	.64	980	270	16
		3/8	.95	260	98	3
		1/2	1.27	560	120	10
	M-2	1/4	.64	100	15	2
		3/8	.95	240	71	3
		1/2	1.27	690	280	11
	P	1/4	.64	600	200	50
		3/8	.95	220	65	3
		1/2	1.27	1 200	640	50
	R	1/4	.64	340	220	80

TABLE 23.—Showing the Effective Voltage Necessary to Arc Over the Surface of a Sample of Phenolic Electrical Insulating Material Between Two 2-cm Brass-Skirted Studs Bolted Through the Sample 2 cm Apart

Material	Grade	Thickness		Volts
		Inch	cm	
Bakelite-Dilecto	XX	1/4	0.64	19 800
	X	1/4	.64	19 800
Continental-Bakelite	CB	1/4	.64	21 100
Bakelite Micarta	32-X and 21-X	1/4	.64	20 000
	323 and 213	1/4	.64	19 700
	21-D	1/4	.64	22 000
Condensite Celoron	10 and 15	1/4	.64	21 000
	20	1/4	.64	27 800
Formica	M	1/4	.64	19 700
	M-2	1/4	.64	20 600
	P	1/4	.64	18 400
	R	1/4	.64	21 000

TABLE 24.—Average Values of Phase Difference and Power Factor at Radio Frequencies of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Phase difference (ψ)	Power factor
		Inch	cm	Degrees	Per cent
Bakelite-Dilecto	XX	1/8	0.32	2.0	3.4
		1/4	.64	2.0	3.6
		3/8	.95	2.1	3.7
		1/2	1.27	2.2	3.8
	X	1/4	.64	1.8	3.2
		3/8	.95	1.9	3.3
		1/2	1.27	1.9	3.3
Continental-Bakelite	CB	1/4	.64	3.8	6.6
Bakelite Micarta	32-X and 21-X	1/8	.32	2.8	4.8
		1/4	.64	3.0	5.2
		3/8	.95	3.5	6.1
		1/2	1.27	2.5	4.4
	323 and 213	1/8	.32	2.2	3.8
		1/4	.64	3.0	5.3
		3/8	.95	2.4	4.2
		1/2	1.27	2.1	3.6
	21-D	1/4	.64	5.4	9.5
		3/8	.95	4.8	8.4
		1/2	1.27	6.7	11.7
Condensite Celoron	10 and 15	1/8	.32	2.1	3.6
		1/4	.64	3.6	6.3
		3/8	.95	2.3	4.1
		1/2	1.27	3.7	6.5
	20	1/4	.64	6.3	11.0
Formica	M	1/16	.16	2.5	4.4
		1/8	.32	3.2	5.6
		1/4	.64	2.7	4.7
		3/8	.95	3.2	5.7
		1/2	1.27	3.2	5.6
		1	2.54	3.4	6.0
	M-2	1/4	.64	4.6	8.0
		3/8	.95	3.1	9.1
		1/2	1.27	3.4	5.9
	P	1/4	.64	3.7	6.5
		3/8	.95	2.6	4.5
		1/2	1.27	2.4	4.2
	R	1/4	.64	4.5	7.9

TABLE 25.—Comparison of Average Phase Difference and Per Cent Power Factor of First Samples and More Recent Samples of Formica

Samples received	Approximate thickness		Average phase difference (ψ)	Average power factor
	Inch	cm	Degrees	Per cent
Early (1917–18)	1/4	0.64	6.4	11.2
Do	1/2	1.27	3.6	6.3
Recently (1919)	1/4	.64	2.5	4.4
Do	1/2	1.27	2.6	4.5

TABLE 26.—Average Values of Dielectric Constant at Radio Frequencies of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Dielectric constant (K)
		Inch	cm	
Bakelite-Dilecto	XX	1/8	0.32	4.5
		1/4	.64	5.3
		3/8	.95	5.3
		1/2	1.27	5.6
	X	1/4	.64	5.3
		3/8	.95	5.5
		1/2	1.27	5.6
Continental-Bakelite	CB	1/4	.64	5.3
Bakelite Micarta	32-X and 21-X	1/8	.32	5.4
		1/4	.64	5.8
		3/8	.95	5.9
		1/2	1.27	6.0
	323 and 213	1/8	.32	5.5
		1/4	.64	6.2
		3/8	.95	6.0
		1/2	1.27	6.0
	21-D	1/4	.64	6.6
		3/8	.95	6.7
		1/2	1.27	6.1
Condensite Celoron	10 and 15	1/8	.32	5.9
		1/4	.64	6.9
		3/8	.95	6.4
		1/2	1.27	7.2
	20	1/4	.64	6.8
Formica	M	1/16	.16	5.7
		1/8	.32	5.2
		1/4	.64	5.1
		3/8	.95	5.6
		1/2	1.27	5.8
		1	2.54	6.1
	M-2	1/4	.64	5.7
		3/8	.95	6.1
		1/2	1.27	5.5
	P	1/4	.64	6.0
		3/8	.95	5.8
		1/2	1.27	5.6
	R	1/4	.64	6.5

TABLE 27.—Average Values of Ultimate Strength and Modulus of Elasticity (Tensile) of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Ultimate strength	Variation	Modulus of elasticity ÷1000	Variation
		Inch	cm	Lbs./in.²	Per cent	Lbs./in.²	Per cent
Bakelite-Dilecto	XX	1/4	0.64	13 800	9	1510	.....
		3/8	.95	12 700	7	.....	.....
		1/2	1.27	11 900	15	.....	.....
	X	1/4	.64	15 500	25	.....	.....
		3/8	.95	18 600	30	2120	26
		1/2	1.27	18 600	23	2120	41
		1	2.54	18 400	21	2060	32
Continental-Bakelite	CB	1/4	.64	9 400	8	.....	.....
		1/2	1.27	8 000	1	.....	.....
Bakelite Micarta	32-X and 21-X	1/4	.64	10 800	13	.....	.....
		3/8	.95	11 000	12	.....	.....
		1/2	1.27	10 900	14	.....	.....
	323 and 213	1/4	.64	16 400	20	.....	.....
		3/8	.95	16 500	16	.....	.....
		1/2	1.27	16 800	11	.....	.....
	21-D	1/4	.64	8 300	15	.....	.....
		1/2	1.27	9 500	3	.....	.....
Condensite Celoron	10 and 15	1/8	.32	11 200	33	.....	.....
		1/4	.64	10 700	23	.....	.....
		3/8	.95	11 100	34	.....	.....
		1/2	1.27	11 500	25	.....	.....
		1 1/16	3.02	17 300	11	.....	.....
	20	1/4	.64	8 200	4	.....	.....
		1/2	1.27	7 500	4	.....	.....
Formica	M	1/4	.64	11 400	9	.....	.....
		3/8	.95	14 200	4	.....	.....
		1/2	1.27	12 200	11	.....	.....
	M-2	1/4	.64	13 900	16	1720	.....
		3/8	.95	12 700	20	.....	.....
		1/2	1.27	12 400	17	1730	4
		1	2.54	13 800	10	2410	17
	P	1/4	.64	18 300	35	.....	.....
		3/8	.95	19 300	32	.....	.....
		1/2	1.27	17 000	36	2260	33
	R	1/4	.64	10 400	4	.....	.....
		3/8	.95	8 900	12	.....	.....
		1/2	1.27	10 400	2	.....	.....

TABLE 28.—Average Values of Modulus of Rupture and Modulus of Elasticity (Transverse) of Phenolic Electrical Insulating Material

Material	Grade	Thickness		Modulus of rupture	Variation	Modulus of elasticity ÷ 1000	Variation
		Inch	cm	Lbs./in.²	Per cent	Lbs./in.²	Per cent
Bakelite-Dilecto	XX	1/4	0.64	16 600	7	1290	.....
		3/8	.95	20 700	.....	1340	.....
		1/2	1.27	16 600	4	.....	.....
	X	1/4	.64	22 000	30	.....	.....
		3/8	.95	24 500	26	2370	.....
		1/2	1.27	21 600	.....	1440	.....
Continental-Bakelite	CB	1/4	.64	13 800	2	.....	.....
		1/2	1.27	13 500	.....	.....	.....
Bakelite Micarta	32-X and 21-X	1/4	.64	16 200	10	1470	.....
		3/8	.95	15 000	10	1050	.....
		1/2	1.27	17 400	3	.....	.....
	323 and 213	1/4	.64	20 600	14	2060	.....
		3/8	.95	18 000	6	1150	.....
		1/2	1.27	25 800	20	.....	.....
	21-D	1/4	.64	14 100	2	.....	.....
		1/2	1.27	13 700	5	.....	.....
Condensite Celoron	10 and 15	1/4	.64	15 500	20	.....	.....
		3/8	.95	15 000	22	.....	.....
		1/2	1.27	15 200	38	.....	.....
		1 1/16	3.02	17 700	6	.....	.....
	20	1/4	.64	12 000	0	.....	.....
		1/2	1.27	10 200	18	.....	.....
Formica	M	1/4	.64	16 800	9	1120	.....
		3/8	.95	18 300	12	1420	.....
		1/2	1.27	18 100	3	.....	.....
	M-2	1/4	.64	17 000	15	1480	.....
		1/2	1.27	17 700	16	1380	5
	P	1/4	.64	18 800	4	.....	.....
		3/8	.95	24 300	23	.....	.....
		1/2	1.27	21 100	28	1410	.....
	R	1/4	.64	14 000	5	.....	.....
		3/8	.95	14 500	9	.....	.....
		1/2	1.27	16 800	4	.....	.....

TABLE 29.—Average Values of Brinell Hardness Numerals of Phenolic Electrical Insulating Material Tested at Two Temperatures

Material	Grade	Thickness		Brinell hardness numerals tested at—	
				20–30° C	50° C
		Inch	cm		
Bakelite-Dilecto	XX	3/8	0.95	42	37
		1/2	1.27	40	39
	X	3/8	.95	34	31
		1/2	1.27	23	20
Continental-Bakelite	CB	1/4	1.27	32	30
Bakelite Micarta	32-X and 21-X	3/8	.95	39	34
		1/2	1.27	39	34
	323 and 213	3/8	.95	35	33
		1/2	1.27	34	30
	21-D	1/2	1.27	37	32
Condensite Celoron	10 and 15	1/2	1.27	38	35
	20	1/2	1.27	38	32
Formica	M	3/8	.95	35	33
		1/2	1.27	37	34
	M-2	3/8	.95	44	40
		1/2	1.27	45	42
	P	1/2	1.27	38	34
	R	1/2	1.27	39	34

TABLE 30.—Average Values of Scleroscope Hardness of Phenolic Electrical Insulating Material Tested at Two Temperatures

Material	Grade	Thickness		Scleroscope hardness tested at—	
				20–30° C	50° C
		Inch	cm		
Bakelite-Dilecto	XX	3/8	0.95	88	83
		1/2	1.27	87	83
	X	3/8	.95	73	65
		1/2	1.27	64	63
Continental-Bakelite	CB	1/2	1.27	58	58
Bakelite Micarta	32–X and 21–X	1/2	1.27	83	80
	323 and 213	3/8	.95	83	78
		1/2	1.27	79	75
	21–D	1/2	1.27	75	70
Condensite Celoron	10 and 15	1/2	1.27	85	82
	20	1/2	1.27	87	82
	30	1/4	.64	75	74
Formica	M	3/8	.95	84	80
		1/2	1.27	85	79
	M–2	3/8	.95	94	93
		1/2	1.27	86	85
	P	1/2	1.27	86	82
	R	1/2	1.27	70	64

TABLE 31—Average Values of Resistance to Impact, Expressed in Foot-Pounds, of Phenolic Electrical Insulating Material as Determined by the Use of Standard, Square, Notched Specimens

Material	Grade	Thickness		Impact strength
		Inch	cm	Ft.-lbs.
Bakelite-Dilecto	XX	1/2	1.27	0.7
	X	1/2	1.27	.9
Continental-Bakelite	CB	1/2	1.27	1.2
Bakelite Micarta	32–X and 21–X	1/2	1.27	.2
	323 and 213	1/2	1.27	.8
	21–D	1/2	1.27	2.1
Condensite Celoron	10 and 15	1/2	1.27	.4
	20	1/2	1.27	1.0
Formica	M	1/2	1.27	.3
	M–2	1/2	1.27	.3
	P	1/2	1.27	1.5
	R	1/2	1.27	2.9

TABLE 32.—Average Value of density of and Percentage by Weight of Moisture Absorbed in 24 Hours by Phenolic Electrical Insulating Material

Material	Grade	Thickness		Density	Water absorbed in 24 hours
		Inch	cm	g/cm³	Percentage by weight
Bakelite-Dilecto	XX	1/4	0.64	1.34	0.30
		3/8	.95	1.34	.17
		1/2	1.27	1.36	.16
	X	1/4	.64	1.34	2.35
		3/8	.95	1.37	.74
		1/2	1.27	1.31	2.20
Continental-Bakelite	CB	1/4	.64	1.32	.46
		1/2	1.27	1.29	.52
Bakelite Micarta	32-X and 21-X	1/4	.64	1.36	.38
		3/8	.95	1.34	.38
		1/2	1.27	1.36	.24
	323 and 213	1/4	.64	1.37	1.09
		3/8	.95	1.37	.89
		1/2	1.27	1.37	.67
	21-D	1/4	.64	1.36	1.09
		1/2	1.27	1.36	.74
Condensite Celoron	10 and 15	1/4	.64	1.40	.32
		3/8	.95	1.43	.24
		1/2	1.27	1.41	.22
	20	1/4	.64	1.34	.32
		1/2	1.27	1.35	.46
Formica	M	1/4	.64	1.36	.39
		3/8	.95	1.37	.21
		1/2	1.27	1.35	.19
	M-2	1/4	.64	1.34	.52
		3/8	.95	1.33	.76
		1/2	1.27	1.36	.20
	P	1/4	.64	1.38	.77
		3/8	.95	1.41	.53
		1/2	1.27	1.35	.52
	R	1/4	.64	1.38	1.47
		3/8	.95	1.37	1.38
		1/2	1.27	1.39	.81

V. DISCUSSION OF RESULTS

1. UNIFORMITY OF PROPERTIES

SAMPLE TO SAMPLE.—Variations in electrical and other properties of materials of the same manufacture and grades are clearly shown in the tabulated data on pages 524 to 533. In some cases these variations are by no means unimportant. The causes of these variations are not easily traced. Variations in electrical and other properties of these insulating materials may be due to variations in the phenolic varnish, the paper, the atmospheric conditions at the time of manufacture, or the way the material is handled during manufacture.

SAMPLES SUBMITTED VS. SAMPLES PURCHASED.—It has been gratifying to find that, in general, the samples of laminated phenolic materials purchased in the open market have checked quite closely in electrical and other properties the samples submitted by the various companies. In one instance a sheet of

laminated material was purchased from a Washington firm, who sold the sheet as Bakelite Micarta, grade 21–X. Our tests showed quite clearly that this sheet was grade 213 Bakelite Micarta. This emphasizes the fact previously pointed out that the purchaser can not determine the grade of the material from appearance.

Sheets of Formica, grade M, which were purchased for laboratory use about this Bureau, have, in general, shown electrical properties rather better than the samples furnished by the manufacturer for testing.

UNIFORMITY OF SHEET.—Tests of the uniformity of a sheet of material were made by measuring the volume resistivity of pieces cut from various parts of the sheet. The results are given on page 598. Similar tests were made on phase difference. This was measured for a piece taken from the center and opposite corners of a sheet taken from stock, B. S. No. 20–256, Formica M. Pieces 25 by 31 cm (10 by 12 inches) were cut from sheet 61 by 92 cm (24 by 36 inches).

TABLE 33.—Phase Difference and Dielectric Constant of Three Portions of a Standard Size (24 by 36 inches) Sheet of Formica, Grade M

Portion of sheet from which sample was taken	Wave length (λm)	Phase difference (ψ)	Dielectric constant (K)
	Meters	Degrees	
Center	1021	1.77	4.71
	1395	1.73	4.74
	1925	1.70	4.77
Corner	1015	1.77	4.67
	1388	1.79	4.70
	1919	1.70	4.74
Diagonally opposite corner	1017	1.83	4.68
	1390	1.84	4.70
	1920	1.79	4.74

The variations are somewhat greater than the limit of error of the measurement.

2. PHASE DIFFERENCE

On page 512 several reasons were shown why power factor or phase difference at radio frequencies was given special emphasis among the properties measured. To one interested in the development or correct use of an insulating material to be subjected to radio-frequency voltages, the phase difference probably furnishes the best single basis for judgment of such material.

Because all measures of phase difference have been made on a temporarily constructed condenser using the insulating material as a solid dielectric, it is not to be inferred that such materials are actually used for radio condensers or recommended for such use. However, when a solid insulating material is used as a

means of supporting and insulating binding posts, contacts, or wires carrying alternating current, there is in reality a condenser or series of condensers between these conducting pieces with the insulating material as the dielectric. A relatively poor insulating material for radio use is a material that adds resistance to a circuit and causes power loss. For this reason it is of value to have experimental data that will determine the relative superiority of materials in respect to power loss.

In the equation $P=RI^2$, the equivalent resistance (R) of a sample is equal to the watt loss (P) per ampere. However, (R) is not a constant of the material, since it varies with frequency and with the size and shape of the specimen.

Phase difference or power factor assists also in an understanding of some other radio properties of an insulating material. Formula 1 states that phase difference may be expressed as a ratio of the power dissipated in the form of heat to the total power flowing. The effect of the energy lost as heat is cumulative. The initial heating lowers the electrical resistance of the insulating material, this causing greater current conduction and increased heating. Thus, when high voltage are used, the insulating material gradually becomes conductive and a flash-over or breakdown occurs. The phase difference, a property which expresses the heating of the material, is the most important single property in determining the radio-frequency current and voltage that an insulating specimen will stand. It indicates in a comparative way which material should stand longest under high electrical stress. This is discussed further in section V–3, "Voltage effects at radio frequencies."

Effect of Metal Particles in Material.—In comparing some values of phase difference obtained on three samples of laminated phenolic insulating materials of the same grade received at the same time surprising differences of properties in the different thicknesses were observed. The following is a statement of results on the three samples:

TABLE 34.—Effect of Metal Particles in Material

Approximate thickness		Average phase difference (ψ)
cm	Inch	Degrees
0.34	1/8	3.6
.65	1/4	2.2
.98	3/8	2.1

It seemed strange that the first two samples should differ so much, in view of the fact that they were the same grade, made under same conditions, and presumably differed in thickness only. Ordinarily the thinner sheets show a lower phase difference or power loss. After close inspection, however, it was found that many small metallic particles had found their way into the material. It seemed probable that these were sufficient to cause the unusually high phase difference. They may have been present in the particular batch of paper used in making up this sheet of material.

3. VOLTAGE EFFECTS AT RADIO FREQUENCIES

The methods of measuring the radio-frequency flash-over voltage and other voltage effects at radio frequencies upon the various insulating materials have not been worked out as completely as the method of measuring phase difference. It is hoped that more work can be done at this in the future. The results given on page 549 show some differences, although not great, in the makes and grades of material. The data also show a difference in flash-over voltage with time of test. This seems to be another effect of surface-absorbed moisture.

Flash-over voltage is dependent upon the nature of the material, character of the surface, and the shape, size, and spacing of the contacts. Besides the measurements of flash-over voltage, the materials were tested for endurance voltage, as described in a Bureau publication mentioned on page 506. As explained there, the measurements of endurance voltage can not be so readily presented nor interpreted as the flash-over voltage, and hence are not included in this paper. The results run quite parallel to those in flash-over voltage and are a fairly good index of the voltage properties in general.

Measurements of breakdown voltage at radio frequencies were not made in any systematic way. This occurs at very much lower voltages than for low frequencies. The breakdown voltage is of less practical importance than flash-over voltage, since the metal parts on insulating panels in radio apparatus are usually so placed that high voltage will produce failure across the surface rather than through the material.

Breakdown voltages, and to a somewhat smaller extent all the voltage effects at radio frequencies, are a function of the heating of the insulating material. The failure of the insulation is usually not a definite puncture but is instead a loss of insulating and

dielectric properties. That is, the material heats up and becomes a conductor, so that it no longer functions as a dielectric. This research has shown that a simple statement of voltage for breakdown or any other effect at radio frequencies is meaningless without accompanying specification of a number of other factors. The experiments made indeed indicate that the phase difference is fully as good a criterion of the breakdown point as a single value of voltage. The fact is that the phenomenon of breakdown depends on the dielectric constant, phase difference, thermal conductivity, specific heat, temperature at which material carbonizes, disintegrates, and melts, as well as frequency, voltage, and time of application. The breakdown voltage differs for different shape and size of sample, shape, size, and location of electrodes, frequency, time of application of voltage, and characteristics of the source supplying the voltage. It depends very largely upon the phase difference, because for a given voltage the heat produced in the material is greater the greater the phase difference, and consequently the more rapidly does the material heat and a failure occur for a given applied voltage. Materials which have high phase difference generally show low values in the voltage tests.

4. VOLUME RESISTIVITY

The values of volume resistivity of the laminated phenolic insulating materials vary widely also—that is, different samples of the same grade in some cases vary by a factor of about 100 in volume resistivity values. Rather wide variations were also found when measurements were made at different places on a comparatively large sample. The sketch and results below show this:

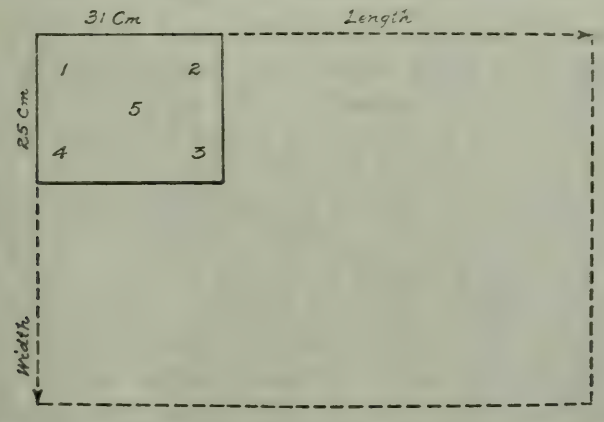

FIG. 54.—*Diagram of places where volume resistivity measurements were made on a sample 25 by 31 cm*

TABLE 35.—Volume Resistivity Values[a] at Five Positions on a 25 by 31 cm sample of Phenolic Electrical Insulating Material

Position	Volume resistivity
	Ohm-cm $\times 10^3$
1	500
2	130
3	130
4	680
5	300

[a] All volume resistivity measurements were made at room temperature and humidity.

5. SURFACE RESISTIVITY

The curves shown on pages 550 to 561 were plotted from the data given in the summary tables on pages 524 to 533. The dates of tests recorded in column 5 apply only to the data in columns 6 to 11, inclusive. However, the resistivity data in the table are recorded chronologically. That is to say, where two or more resistivity measurements have been made on the same sample, the values appear in the summary table in chronological order.

Only a few of the first curves shown will be discussed here. The curves for B. S. sample No. 164 (Fig. 29, p. 51) are rather uniform. Two test samples (A and B) were cut from the same sheet and tested twice (about 50 days apart). The earlier data are represented by the two upper curves. The curves for B. S. samples Nos. 61 and 62 (Fig. 28, p. 50) represent data taken about one year apart, the upper curves being for the earlier data. In fact, in all cases where the same sample has been tested twice, the earlier surface resistivity values are the higher. This can be ascertained by comparing the curves and the data on pages 524 to 533.

By comparing the upper curves (Fig. 28, p. 50) for B. S. samples Nos. 61 and 62 it might appear that Bakelite-Dilecto, grade X, was equivalent to hard rubber (see Fig. 39, p. 561) in surface resistivity. However, if the average values of surface resistivity of hard rubber at a 25 per cent humidity be compared with a similar average on the Balelite-Dilecto, the hard rubber will show a much higher value, in the ratio of about 10^{15} to 10^{12}. At 84 per cent humidity the ratio of surface resistivity of hard rubber to the X grade, Bakelite-Dilecto sample, is about 3×10^{10} to 1×10^{8}.

Some of the second-grade samples (Bakelite-Dilecto, X, and Bakelite Micarta, 323 and 213) show a higher surface resistivity at the lower humidities than the first grades. This may be owing

to the smaller percentage of varnish in the second-grade materials or to the slightly rougher surfaces on such grades.

A table of average values of surface resistivity of the various kinds, grades, and thicknesses of laminated phenolic insulating material is given on page 587. It is evident from these data that the surface resistivity of a particular grade of material varies within wide limits. The following table shows the observed range of variation:

TABLE 36.—Range of Variation in per cent from the Lowest to the Highest Value of Surface Resistivity at 25 per cent Relative Humidity for Phenolic Electrical Insulating Material Irrespective of Thickness

Material	Grade	Variation
		Per cent
Bakelite-Dilecto	XX	680
	X	11 000
Bakelite Micarta	32–X and 21–X	700
	323 and 213	210
Condensite Celoron	10 and 15	130
Formica	M	380
	M–2	690
	P	550

6. MOISTURE ABSORPTION.

The effect of moisture contained in or absorbed by an insulating material is now considered very carefully. The effect on permanence of shape and mechanical properties may be temporarily disregarded for the more serious effect on insulation resistance and power loss.

By referring to the itemized data on pages 524 to 533 or to the summary tables on page 593, one can see the different amounts of water absorbed by the materials of different grade. As an example, the average per cent of water absorbed by a sample of Bakelite-Dilecto, grade XX, 5 by 10 by 0.64 cm, is 0.30. The amount absorbed by a sample of the same dimensions but of grade X is 2.35 per cent. The grade XX material is advertised to be made from paper saturated with Bakelite varnish and grade X from paper coated with the varnish. The data show less moisture to have been absorbed by the saturated paper material. This same comparison can be made between Bakelite Micarta, grades 32–X (21–X) and 323 (213), or between Formica, grades M and P. The other grades and kinds are not so readily compared because either the binder or filler (base), or both, may be different. Consult pages 508 and 509 for this difference.

The percentages of moisture absorbed by the different kinds and grades of material can not be compared directly unless samples of the same size and thickness are used. Where samples of the same grade are considered, it is evident, from most of the data given on page 593, that the percentage of moisture absorbed apparently decreases as the thickness increases. This is because the percentage values are based on weight and the weight of the samples does not increase in proportion to the absorbing area of samples of different thicknesses. Future measurements of moisture absorption expressed in grams per square centimeter of cut and uncut surface will be independent of sample size and thickness.

The impression that any of the laminated phenolic insulating materials are strictly nonhygroscopic is erroneous. One has only to oven dry a small piece of this material (5 by 5 by 0.64 cm) and try to weigh it in the open atmosphere by using a very sensitive chemical balance to determine this point. The dried sample immediately absorbs moisture (in minute quantities) from the air and renders a permanent balance difficult. If one weighs the sample before drying and compares that with some momentary dry weight, there is an evident loss in weight. If one claims that this loss in weight is due to passing off of vapors from continued chemical reaction, then the impression that such materials are unaffected by heat is erroneous. This is discussed more fully under "Thermal properties" below.

7. TENSILE STRENGTH

Effect of Grain.—The apparent effect of the grain of the paper used in these insulating materials has been mentioned on page 511. The data given on pages 524 to 533 in the columns headed ultimate strength in most cases are followed by x or y. When the samples were cut from the large sheets, those cut in one direction were labeled x and those cut at a right angle to x were labeled y. It is practically impossible to know the direction of the grain of some of the materials before testing, so the labels x and y refer only to different directions of cutting. This explains why some of the x values are greater than the y values.

The data mentioned above shows a greater apparent effect of grain for those grades that are recommended for mechanical work. Such grades are designated in this report as second grade (see p. 617). There is a difference of from 30 to 100 per cent in the x and y data for these grades of material.

It is interesting to notice that the canvas base materials (see p. 590) do not have as great tensile strength as the paper or fiber base materials. This is contrary to the first beliefs of many. There is a quite apparent explanation of this lower strength in the fact that, although there is greater strength in a single canvas sheet than in a single paper sheet, a single sheet of canvas is so much thicker that in a built-up piece of canvas base insulating material there are fewer binding cellulose fibers in a given space than in the paper base material. The canvas base material does have greater resistance to impact. This is discussed in section V–10, page 604.

Ductility.—The difficulty met in determining the elongation of the tensile test specimen under stress has been stated in the paper mentioned on page 506. Values of elongation are, therefore, not determined at more stresses than are sufficient to locate the proportional limit. The last points plotted in the curves on page 562, do not represent ultimate strength. By referring to these curves (Fig. 40) on page 562 one will notice that the greatest total elongation or deformation of any of the specimens is about 0.019 of an inch in 2 inches, while the average of the specimens plotted is about 0.013 of an inch in 2 inches.

8. TRANSVERSE STRENGTH

The method of making transverse or cross-bend strength tests on laminated insulating materials is described and illustrated in another Bureau publication mentioned on page 506.

The curves (Figs. 42 to 51, inclusive) on pages 564 to 573 were plotted from data obtained by the screw-press method of applying the load. The curves (Fig. 41) on page 563 differ from the curves shown in Figs. 42 to 51, in that in Fig. 41 fiber stress has been plotted against deflection instead of load in pounds against deflection. By plotting the data in this way the transverse proportional limit is obtained and is marked by the point at which the curve deviates from a straight line.

Not enough curves are shown here to give a complete comparison of the modulus of rupture or maximum fiber stress of all the materials. Curves on B. S. samples Nos. 18 and 24, 19 and 25, 20 and 26 show quite well the effect of grade on the modulus of rupture. One of each of the three pairs of samples is Bakelite Micarta, grade 32–X, the other being grade 323. As outlined on page 617, grade 323 is classed as second-grade material but

possesses better mechanical properties. It is interesting to notice also that the moduli of rupture of one-fourth inch Bakelite Micarta, grades 32–X and 323 (B. S. samples Nos. 19 and 25) are higher than the values for the corresponding grades in three-eighths inch thick material.

As stated above, the curves in Figs. 42 to 51 were plotted from data found by using the screw-press method of applying the load. From these particular curves it is not feasible to make an intercomparison of kinds and grades of insulating material except for shape of curve, because the samples were not all cut the same width. The actual load in pounds is plotted against deflection, so the area of cross section does not enter. If the actual moduli of rupture or moduli of elasticity values are desired on these samples, reference may be made to the tables on pages 524 to 533.

It is quite apparent that, by using the screw-press method of applying the load and a platform scale for determining the magnitude of the load, the measured load is entirely dependent on whether the sample sustains or yields under the applied load. This explains why some of the load-deflection curves for the canvas base materials run part of their course about parallel with or even approach the ordinate with an apparent increase in load. The curves for the paper and fiber base phenolic insulating materials have a much steeper curve throughout, being less flexible than the canvas base materials.

The first curve on Fig. 45 shows the effect of failure of the outer layers of canvas under tension. The sample finally broke under a load lower than the maximum load previous to the failure of the lower strata.

The curves on pages 570 to 573 (Figs. 48 to 51) were plotted from data obtained by suspending a known mass from the test sample midway between the supports and measuring the deflection at the center in inches. This method is called the dead-weight method here. In many ways it is superior to the screw-press method. The load is independent of the yielding of the sample under stress. This is shown by the fact that all curves by this method have a continuous and more or less gradual upward trend. It is impossible by this method to get a curve similar to the first curve in Fig. 45.

It is worthy of note that all of these curves for samples of like thickness are directly comparable, in that all samples were

machined quite accurately to the same width. It does not seem necessary to analyze particular curves in this group. The effect of grade on the magnitude of applied load at rupture and the effect of grade on the ultimate yield or deflection is quite clearly pictured. Reference is again made to the differentiation of grades on page 508. Attention is called to the first and third curves in Fig. 49, page 571. These samples were both more or less poorly laminated. The magnitude of the possible suspended load and computed modulus of rupture is correspondingly lowered.

9. HARDNESS

The hardness of the laminated phenolic insulating materials is mainly dependent on the amount of varnish (phenol condensation product) in the material and upon the press pressure and length of time the material is cured in the press. In the event one is considering sheet-asbestos-filled phenolic insulating materials, then it would be necessary to include filler as one of the factors influencing hardness. The effect of the various papers used may be neglected, however, in their bearing on hardness.

Hardness and brittleness are associated in some respects. Brittleness affects the impact strength or shock-absorbing property of a material. With this in mind, the impact strength data on Bakelite-Dilecto, grades XX and X, and Bakelite Micarta, grades 32–X and 323 (p. 592), seem to bear out the conclusion that the amount of phenol varnish affects hardness, other factors being equal. Grades XX and 32–X, which contain more varnish than grades X and 323, have lower impact strength values and higher hardness values than grades X and 323.

It is quite apparent that the press-pressure temperature and length of curing will affect the hardness of these materials, the effect of pressure being more apparent than temperature and duration of curing. A more complete chemical reaction caused by higher temperature and longer curing renders the phenolic varnish more hard and brittle.

The data on pages 524 to 533 and page 591 show that the Brinnel hardness numerals of all the materials have been lowered somewhat by heating the material to 50° C. The values of hardness (B. h. n.) of the materials at 50° C are from 2 to about 16 per cent lower than at 20–30° C. This is in accord with the conclusions drawn in section V–13, page 607.

10. IMPACT STRENGTH

The determination of impact strength of insulating materials with our present equipment we have found rather difficult. The impact testing machines in our strength-of-materials laboratory are all designed for testing of metals. They are, therefore, of larger capacity than is advisable for the more brittle insulating materials. When the pendulum hammer was drawn to some workable angular distance from the position of rest, so much potential energy was stored in the pendulum hammer that when released the hammer would break the sample and swing too far beyond its position of equilibrium. More accurate results are obtained when the total kinetic energy of the pendulum hammer exceeds but little the energy absorbed by the sample during fracture.

The data shown on page 574 divides the phenolic insulating materials reported into three classes with respect to impact strength. The following classes are in the descending order of strength, and the grade names are alphabetical.

Class 1 contains Bakelite Micarta, grade 21–D; Condensite Celoron, grade 20; Continental-Bakelite; and Formica, grade R.

Class 2 contains Bakelite-Dilecto, grade X; Bakelite Micarta, grade 213; and Formica, grade P.

Class 3 contains Bakelite-Dilecto, grade XX; Bakelite Micarta, grades 21–X and 32–X; Condensite Celoron, grades 10 and 15; and Formica, grades M and M–2.

The above classification does not imply that the materials in a certain class have an equal impact strength, but that the several grades manufactured by each of the four companies when intercompared fall into these classes.

It is interesting to notice that even by using testing machines having large capacity the grades of material having no dissimilarity, except that of color or kind of varnish, the values of impact strength are almost identical. Condensite Celoron, grades 10 and 15, and Formica, grades M and M–2, show this.

It has been mentioned in section V–7 above that the canvas-base materials have lower tensile strength than the paper or fiber base materials. The data on page 574 show, however, that the impact strength of the canvas-base material of a certain make is from 2.5 to 10 times as great as the grade having the best electrical properties in that same make. As an example, Bakelite Micarta, grade 21–D, has over 10 times greater impact strength

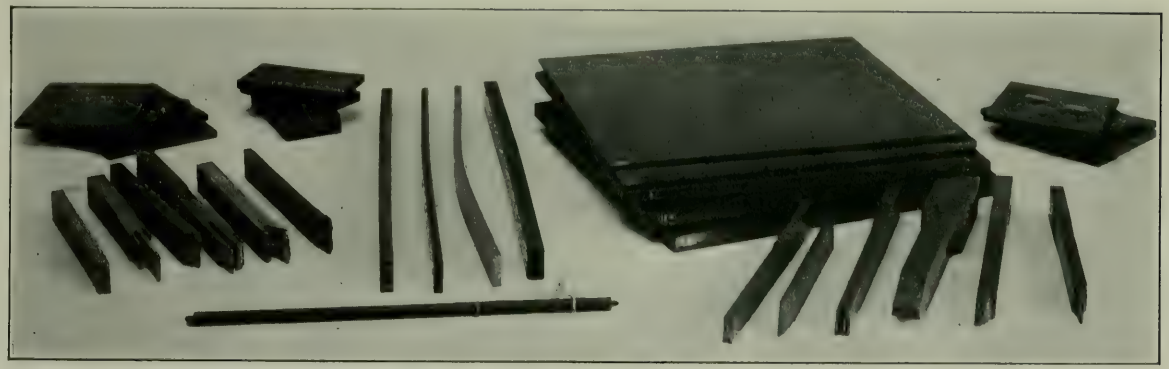

FIG. 55. *Test samples for determination of thermal expansion, tensile strength, transverse strength, permanent distortion, phase difference, high-voltage high-frequency endurance, surface resistivity, and moisture absorption*

than grade 32–X. Likewise, Formica, grade R, has an impact strength almost 10 times higher than grade M. Because of this shock-absorbing property of the canvas-base materials and other good mechanical properties they find a ready use in the manufacture of pinions, racks, and other such parts.

11. PERMANENT DISTORTION

The data given on pages 575 and 576 on permanent distortion or warp under stress is not as complete or conclusive as we had hoped it would be. By referring to the method of determining permanent distortion as described in the Bureau publication mentioned on page 506 it will be seen that a complete test on the 52 samples would have required several months.

The various increments of added load were not small and numerous enough to plot curves that would show the relation of stress applied for a specified time to permanent distortion or deflection. However, the data do give a general idea of how strips of these phenolic insulating materials yield under the stress of a dead weight. No attempt will be made to show which manufacturer's material is the better in this respect. The data are not sufficient.

The data given on the sag of panels under stress are practical (see p. 577). They show that a three-eighths inch thick sample 18 by 24 inches when loaded between V blocks 22 inches apart is apparantly perfectly elastic to about 400 pounds applied for 24 hours. A half-inch sample seemed perfectly elastic to about 600 pounds applied for 24 hours. The latter sample took a permanent set of 0.156 inch when a load of about 800 pounds was applied for 24 hours.

Natural Warp.—The manufacturer of instrument panels or other parts requiring sheets of insulating material of fair dimensions often has greater concern over the natural warp of the sheets than over later warp or distortion under stress. As reported on page 578 some of the samples as received from the manufacturers had a natural warp of 2 cm in a distance of 1 m. For many uses the sheet of material must be free from this natural warp.

12. MACHINING QUALITIES

The summary tables on pages 579 to 580 is the result of sifting about 500 single page reports covering the opinions of the two mechanics after machining as many samples of insulating material.

The detailed reports are interesting and satisfactory. It is quite evident that but few of the details can be given here.

In so far as possible black materials only were used. This made it practically impossible to identify the several materials. These black samples were numbered in such a way as to give no indication of the kind of material or grade. Two or more samples of each grade were given to machinist L and one of each to machinist R.

It is interesting to see how generally consistent L's reports were. If a given grade of material was represented by two samples arbitrarily numbered 9DX and AB, as a rule he decided either that both worked equally well in a certain test or that they worked very similarly. There were, however, some inconsistencies in the machinists' reports.

The mechanics' reports on test No. 6 showed that the majority of the samples drilled undersize. In some cases the hole diameter was 0.005 inch less than the drill size. This made some of the samples more difficult to tap for the one-fourth inch 20 thread.

Tests Nos. 4, 8, and 9 are particularly severe. Test No. 4, die threading, determines how well the laminations adhere. Since the samples were cut from laminated sheet material and lathe turned, the die cut threads in two ways of the laminations. In many cases the thread would not hold in the cross-lamination direction.

Test No. 8 would have been less severe if the samples had been clamped in a vise before tapping. This would have supported the laminations but would not have tested the relative strengths of adhesion.

The samples in test No. 9 would have had more perfect corners and edges if the samples had been backed where the shaper tool left the cut. This was intentionally omitted. All the samples stood this test surprisingly well.

A summary of the results of this series of tests may be given as follows:

For general machine work there hardly seems to be a preference among the grades of material tested.

Where the machining work requires strongly adhered laminations, the first-grade materials are better. These grades usually have a higher percentage of varnish.

The materials with the lower per cent of varnish affect the machine tool the least.

Paper and canvas-base materials differ in machining qualities. The experience which the particular machinist has had with this type of material has more to do with the finished product than has the kind or grade of material.

13. THERMAL PROPERTIES

The results of measurements on thermal expansion are quite completely given on pages 581 to 583. It may be concluded from the changes in dimensions caused by high temperatures that when a phenolic insulating material is to be used at temperatures above 60° C it should be carefully ascertained that the changes of dimensions will not injuriously affect the operation of the device in which it is used. For such temperatures these materials would not be suitable in delicate instrument parts but would be suitable for such devices as a magneto distributor cap and similar parts.

Miscellaneous Temperature Effects.—When samples of the laminated material were heated in a closed electric muffle furnace, three stages of destruction were noticed, and in the following order: (1) Blistering of the surface; (2) cracking within and along the body; (3) smoking, with the odor of phenol and of charring organic matter.

The sample of Bakelite-Dilecto, grade XX, Bakelite Micarta, grade 32–X, and Formica, grade M (the only grades which were given this test), all blistered at about the same time at about 235° C. The second grade materials (Bakelite-Dilecto, grade X, and Bakelite Micarta, grade 323) started to blister at about 185° C.

The second stage of destruction has no definite limits of temperature but comes approximately between 200 and 400° C. The second-grade materials precede the first-grade in the tendency to curl and split. At about 500° C all the materials began to glow and burn to ash. This is equivalent to the third stage prolonged.

14. EFFECTS OF ACID AND ALKALI

The reasons for making this test have been given on page 515 of this paper, and the method can be found in the Bureau of Standards publication mentioned on page 506.

Acid.—It is evident that either sulphuric acid or caustic soda (NaOH) would attack cellulose in the form of rag or wood pulp base paper. This is a test of how well the phenolic condensation product (varnish) protects the cellulose from the acid and caustic solution and how the varnish itself resists the action of the acid

and caustic. It appears from the data given on page 584 that in all cases the samples have increased in weight when immersed in a 22 per cent solution of sulphuric acid for 48 hours. This shows that these materials are somewhat permeable. It is interesting to notice, however, that the first-grade materials of each make show less change in weight and little or no change in hardness after being immersed in the acid. The other grades contain a lower per cent of varnish and show a resulting greater increase in weight and decrease in hardness. The hardness tests point to the probability that in the first-grade materials the fluid of lower specific gravity (water) has been absorbed, while water and acid have been absorbed by the second-grade materials, since the acid surrounding the cellulose fiber or filler tends to carbonize that fiber and render it soft.

Continental-Bakelite and Bakelite Micarta, 21–D, canvas-base materials, seem to be exceptions, for they are about one point (B. h. n.) harder after immersion in acid than before. This difference is slight and may be due to errors in measuring the diameter of indentation.

Some irregular tests were made on different kinds and grades of laminated phenolic materials using 20 per cent solution of sulphuric acid at 80° C. The samples were immersed in this solution for 48 hours. None of the samples withstood the test. All crumbled in the hardness testing machine.

Pieces of Formica, grade M, have been used in a commercial way in a 10 per cent sulphuric-acid bath at room temperature for about a month. This use is not for the purpose of a test. The pieces were used for about six months and were found to have sufficient insulating and mechanical properties.

ALKALI.—The acid solution mentioned above showed practically no discoloration after the samples had stood in it for 48 hours, while the caustic solution was very much discolored, with a noticeable amount of sediment. It is recognized by the manufacturers of phenolic varnish and resin that such compounds are affected by even weak caustics if time is sufficiently prolonged and are disintegrated by stronger caustics. In comparing the Brinell hardness as shown in the table on page 585 one should bear in mind that only 250 kg pressure was used on the Brinell machine when testing the samples after being subjected to the caustic. The samples were too soft to bear 500 kg. Although pressure (P) enters into

the formula for B. h. n. (formula 9, p. 521), the values of hardness are not directly comparable when different pressures are used.

15. EFFECTS OF SEASON OF YEAR

On Phase Difference.—The results tabulated on pages 524 to 533 show some variations of phase difference of the same sample when tested at different seasons of the year. These changes may be attributed to the ordinary changes of atmospheric conditions. The building in which the insulating materials are kept and tested is heated by hot, dry air. This heat is probably effective from November to March. During the warmer months the windows are open and temperature and relative humidity are more nearly the same as the outdoor air. The autumn months are very humid in this locality. It is evident, then, that since there is a gradual change of moisture conditions from winter to summer there will be changes in the insulating materials. The changes are not visible. These may be only temporary physical changes. Our data do not cover sufficient cycles of seasons to merit an opinion as to permanent changes of any properties.

The effects of season are particularly noticeable in the phase difference of B. S. samples Nos. 5, 8, 14, 18, 146, and 212. As an example, in the tabulated data (p. 526) the phase difference ($\psi°$) of B. S. sample No. 146 is as given in Table 37.

TABLE 37.—Phase Difference Measurements Made Six Months Apart on the Same Sample of Phenolic Electrical Insulating Material

Wave length (λ_m) (in Meters)	Phase difference (ψ)	
	Oct. 21, 1918	Mar. 4, 1919
	Degrees	Degrees
696	4. 28	
1376		3. 71
3482	5. 31	
3420		3. 90

This shows the probable effect of moisture on the sample as tested in October and March. High humidity accompanies large phase difference. These changes are presumably owing to the varying amount of moisture absorbed from the air by the materials.

On Dielectric Constant.—The effect of the season of the year on dielectric constant at radio frequencies is strictly parallel to the effects on phase difference. The measurements of dielectric constant of the insulating material are made simultaneously with

measurements of phase difference. The preceding examples of the change of phase difference of a given sample from season to season are directly applicable to the discussion on the change of dielectric constant.

One additional example will serve as an illustration. Many such examples can be found in the tabulated results on pages 524 to 533.

TABLE 38.—Dielectric Constant Measurements Made on Same Sample on Different Dates, Using Radio-Frequency Current

Date	Wave length (λ_m)	Dielectric constant (K)
	Meters	
Mar. 29, 1919	1919	5.9
Apr. 19, 1919	1963	6.1
Feb. 20, 1920	2027	6.7

On Surface Resistivity.—While no measurements of surface resistivity have been made on samples exposed to an open atmosphere of varying humidity, the same effect has been attained and measurements made on samples using a cabinet in which the humidity could be carefully controlled. The data are given on pages 524 to 533 and summarized on page 587. The effects are very large. It would naturally be expected that a surface property would be more affected by atmospheric conditions than properties of the inner volume of the material such as phase difference and dielectric constant.

16. EFFECTS OF BAKING OR DRYING

On Phase Difference.—The foregoing explanation of the change in phase difference of this type of insulating material with atmospheric humidity is substantiated by the fact that the phase difference of most samples can be lowered by subjecting it to a moderate heat for several hours. The sample is tested again after it has returned to room temperature. The above sample (B. S. No. 146) shows this effect also.

TABLE 39.—Phase Difference Lowered by Baking or Drying Sample

Baking or drying	Date of test	Wave length (λ_m)	Phase difference (ψ)
		Meters	Degrees
After drying 120 hours at about 70° C	Mar. 11, 1919	1264	2.20
After standing 5 months	Aug. 2, 1919	677	2.79

Also B. S. sample No. 5, Table 40.

TABLE 40.—Phase Difference Lowered by Baking or Drying Sample

Baking or drying	Date of test	Wave length (λ_m)	Phase difference (ψ)
		Meters	Degrees
Before baking	Mar. 4, 1918	1025	3.17
	Sept. 20, 1918	672	5.40
After drying 150 hours at about 70° C	Oct. 17, 1918	707	5.71
	Oct. 25, 1918	664	3.79
	Mar. 25, 1919	1002	3.67
	Sept. 20, 1919	1064	5.97

B. S. samples Nos. 7, 60, 61, and 117 show similar results.

On Dielectric Constant.—In accordance with the explanation that the greater part of the change of phase difference with time is owing to surface moisture, it would be expected that when the moisture content is high the effective capacity of the insulating material condenser would be proportionally higher. The dielectric constant should thus tend to decrease as the sample is dried. A part of the change of phase difference and dielectric constant may also be owing to some varying property of the organic constituents of the insulating material. The phenolic insulating materials are rather complex chemically.

One example of the change of dielectric constant of a sample of laminated phenolic material with a greater and lesser amount of surface moisture on the sample is given below. Others are given in the data tables on pages 524 to 533.

TABLE 41.—Dielectric Constant Lowered by Baking or Drying Sample

Baking	Date of test	Wave length (λ_m)	Dielectric constant (K)
		Meters	
Before baking	June 7, 1918	1355	5.6
After baking for 90 hours at about 70° C	Dec. 17, 1918	1597	5.0

17. EFFECTS OF FREQUENCY

On Phase Difference and Dielectric Constant.—The detailed results on pages 524 to 533 give numerous examples of the effect of frequency on phase difference and dielectric constant of laminated insulating materials over a range of radio frequencies. As stated in the heading above the data on pages 524 to 533, the values of phase difference and dielectric constant given there include those at the extreme frequencies only. If five determinations were made, using 500 to 3500 m wave lengths (frequencies, 600 000 to 85 700 cycles per second), the values of phase differ-

ence and dielectric constant would be recorded in these tables for only 500 to 3500 m.

The curves on pages 534 to 548 show the change of phase difference, capacity, and equivalent resistance with frequency, of a few representative samples. These curves have been plotted, using all the frequencies at which the above properties were determined. Values of wave length in meters have been used on the abscissas, but this can be converted to frequency (f) in cycles per second, by the relation,

$$f = \frac{3 \times 10^8}{\lambda_m} \tag{10}$$

The curves of phase difference are derivable from those of capacity and resistance, since phase difference is a function of resistance, capacity, and frequency (see formula 1*a*).

The curves of capacity in micromicrofarads may be converted to curves of dielectric constant (K) by using formula 2 in the form

$$K = \frac{C\,T}{55.047}.$$

The capacity (C) and the thickness (T) may be taken from the curves (T is given more accurately in the tables on pp. 524 to 533).

By glancing at these curves one will notice that the effect of frequency change on different samples of the same grade is not the same. Using the curves shown on pages 534 to 538 it appears that the phase difference of Bakelite-Dilecto increases with frequency. The phase difference of some grades of Bakelite Micarta increases with frequency and of others decreases. Different grades of Formica also have phase difference curves increasing as well as decreasing with frequency, while in Condensite Celoron it increases with frequency. The tests have covered a wave length range of about 500 to 3000 m. It is rather difficult to give the magnitude of the variation of phase difference with frequency or wave length when considering so many samples. Over this range, however, the apparent changes in phase difference are from 2 to 30 per cent. About 75 per cent of the curves show an upward trend with increasing frequency (or decreasing wave length).

In addition to the above-mentioned determinations of phase difference and dielectric constant at radio frequencies, a few measurements of these properties have been made at 100, 500,

and 3000 cycles per second. Average representative values at these frequencies are:

TABLE 42.—Phase Difference and Dielectric Constant at 100, 500, 3000, and 300 000 Cycles per Second

Radio frequency	Phase difference (ψ)	Dielectric constant (K)
Cycles per second:	Degrees	
100	9.0	6.9
500	5.0	6.0
3000	4.0	6.0
300 000	2.8	5.3

The phase difference measuring apparatus used in the laboratory is being improved so as to make possible measurements at any frequency from 3000 to 3 000 000 cycles per second. It is expected that tests can be made at this Bureau on insulating material condensers over the range of 100 to 3 000 000 cycles per second of alternating voltage. More extensive data on the effect of a wide range of frequency on phase difference and dielectric constant can then be given.

18. EFFECTS OF THICKNESS

On Phase Difference.—Some results of our early work on laminated insulating materials of the phenol-methylene type showed a tendency of phase difference or power factor to increase with the thickness of the sample. It is an established fact that the 60-cycle puncture voltage of this type of material does not increase in proportion to thickness, so one might reason that the phase difference might be greater in thicker dielectrics, but our data do not show it sufficiently to merit a conclusion. The change in properties from sample to sample may be sufficient, however, to cover up any change owing to thickness.

Some early measurements of phase difference made on a 2.52 cm (1 inch) thick sample were compared with measurements made on a 0.64 cm (one-fourth inch) thick sample of the same make, grade, and color. The values were lower for the 0.64 cm thick sample. A possible explanation of this difference was thought to be incomplete curing of the phenolic varnish in the center of the thicker sample. To test this belief, a 25 by 31 by 2.52 cm sample was sawed into three samples 25 by 31 by about 0.6 cm, one of which came from the middle of the original slab. As shown in the tabulated results, the thinner samples did have a lower phase

difference, but the sample taken from the center of the original sample shows lower phase difference than the two outside samples. This did not substantiate our beliefs in regard to incomplete chemical reaction and high volatile content in the middle of thicker sheets of insulating material.

TABLE 43.—Phase Difference of Four Samples, the First Being 1 Inch Thick, the Other Three Obtained by Cutting the Original Sample into Three One-Fourth Inch Samples

B. S. sample number	Thickness		Wave length (λ_m)	Phase difference (ψ)	Date of test	Source
	cm	Inch	Meters	Degrees		
3-0.....	2.52	1	459	4.0	Feb. 20, 1919	The original sample
			713	3.3	Feb. 24, 1919	25 by 31 by 2.52 cm
			1078	3.3	Feb. 20, 1919	No cut surfaces
			1375	3.3	.....	
			2756	3.3	Feb. 21, 1919	
3-0-A.....	.64	¼	1027	3.1	Mar. 29, 1919	Outside sheet
			1919	3.3	.....	25 by 31 by 0.64 cm
			3430	3.4	.....	One cut surface
			1038	3.2	Apr. 19, 1919	
			1963	3.5	.....	
			3443	3.7	.....	
			1133	4.7	Feb. 20, 1920	
			2027	5.3	.....	
			3670	5.6	.....	
			2035	5.3	Feb. 24, 1920	
3-0-B.....	.64	¼	960	2.7	Mar. 27, 1919	Inside sheet
			1822	2.8	.....	25 by 31 by 0.64 cm
			3245	2.8	.....	Two cut surfaces
			976	2.6	Apr. 18, 1919	
			1848	2.8	.....	
			3207	2.9	.....	
			1059	4.0	Feb. 20, 1920	
			1886	4.4	.....	
			3383	4.5	.....	
3-0-C.....	.57	¼	983	3.8	Apr. 12, 1919	Outside sheet
			1865	4.0	.....	25 by 31 by 0.57 cm
			3228	4.3	.....	One cut surface
			1855	3.9	Apr. 14, 1919	
			3222	4.1	.....	
			1051	5.1	Feb. 20, 1920	
			1910	5.7	.....	
			3423	6.2	.....	

On Mechanical Properties.—From the data thus far collected thickness of sheet has little or no effect on the mechanical properties of the laminated phenolic insulating materials. By referring to the data on pages 524 to 533 one will notice that in some cases the thicker samples of the same grade show a higher tensile strength, but if the variation of values for different samples of the same thickness and grade are considered also, the probable variation owing to thickness alone is small.

On Moisture Absorption.—As pointed out in the Bureau publication mentioned on page 506, experimental data on percentage by weight of moisture absorbed can not be compared unless samples of the same size and thickness are considered. It is quite

readily apparent, however, that the percentage, by weight, of moisture absorbed increases as the area of the cut surface (and hence thickness of sample) increases. To obtain experimental data on this would necessitate a determination of moisture absorption based on a unit area of cut and uncut surface. Such work would be a separate research in itself and should be undertaken.

19. EFFECTS OF COLOR OR DYE

On Phase Difference.—By consulting the summary of data on pages 524 to 533, one will notice that for some of the materials there is apparently a greater phase difference for the samples containing black pigment. Theoretically, this should be the usual result. The pigment is occasionally lampblack (amorphous carbon), which means that a conducting material is added to the insulating material. There should be little or no change in electrical properties when analine dyes are used.

A careful determination of the effect of dye on phase difference at radio frequencies requires that color be the only characteristic that is changed—a difficult limitation in a factory without an experimental laboratory. The data above mentioned often show quite different values of phase difference of insulating materials of the same make, grade, color, and thickness. Since the materials do differ in this respect, it is difficult to determine how much difference in phase difference is owing to color and how much is owing to process variation.

On Flash-over Voltage and Surface Resistivity.—What has been written above about the variation of phase difference with color is equally true when applied to flash-over voltage at radio frequencies and surface resistivity. The data on pages 524 to 533 show very wide variations of resistivity from sample to sample of the same grade and color, so it is again difficult to separate the differences owing to color and process variation.

20. EFFECTS OF SURFACE FINISH

On Flash-over Voltage and Surface Resistivity.—A determination of the effect of surface finish on flash-over voltage at radio frequencies and surface resistivity is difficult. As pointed out elsewhere in this paper, it is not conclusive to determine these properties on two different samples—one with a highly burnished surface and the other with a dull surface. Such results would be a combination of effects owing to surface and process changes. Such an error could be brought to a minimum provided the manufacturer would fabricate the two samples at the same time, using

the same varnish bath and press the samples together in the hydraulic press. We have not received such samples.

If two test samples are cut from the same burnished sheet, the one having the natural burnished surface and the other a sand-papered or sand-blasted surface, the results would be only an approximation of the effect of surface on these properties. If a dull sample is used, one part could be tested as it is and the other buffed to a polish, but then the heat of friction and buffing paste have added their share of changes.

Theoretically, the flash-over voltage and the surface resistivity should be increased when the sample surface is irregular, because the actual surface distance between metallic contacts is greater. If an etched or like surface is considered, there is also a tendency for congealed moisture to form in globules at the apex of the minute mounds instead of coating the whole surface. It is to be understood that when the electrical properties of an irregular or etched surface (similar to the surface of a copper halftone plate) are compared with plane surfaces all surfaces shall have about the same degree of polishing or burnishing.

21. EFFECTS OF ULTRA-VIOLET LIGHT

On Surface Resistivity.—We have made but few tests using the ultra-violet light as a rapid aging medium. The data given need no further comment. We do not know the number of hours' exposure to sunlight which is equivalent in its effect to 30 hours' exposure to ultra-violet light.

TABLE 44.—Effect of Ultra-violet Light on Surface Resistivity of Phenolic Electrical Insulating Material. Tests Made at 42 Per Cent Relative Humidity (See Also B. S. Sci. Paper No. 234)

Material	Grade	B. S. sample number	Approximate thickness		Surface resistivity	
					Before exposure to ultra-violet light at 42 per cent humidity	After exposure to ultra-violet light for 30 hours at 42 per cent humidity
			cm	Inch	Ohms $\times 10^6$	Ohms $\times 10^3$
Bakelite-Dilecto	XX	14	0.95	3/8	9000	3700
	XX	14	.95	3/8	7500	2700
	XX	11	.64	1/4	4000	1900
Bakelite Micarta	32-X	21	1.27	1/2	400	220
	323	27	1.27	1/2	3000	650
Formica	M	2	1.27	1/2	90	37
	M	2	1.27	1/2	100	45
	M	7-0	.95	3/8	180	5.6

22. EFFECTS OF RATIO OF VARNISH TO PAPER

ON PHASE DIFFERENCE.—There was an attempt made to analyze the effect of the per cent of absorbed phenol varnish on the phase difference of the sample. Such a test has many difficulties. The ratios of varnish to paper of the samples here considered were determined by the manufacturer making the insulating material and were only approximate. There was no attempt made to calculate the ratio of solid resin to paper, which necessitates a correction for the volatile matter escaping in the drying and pressing.

There is no simple analytic method of making a percentage composition test after the insulating material is made, for then the varnish has passed to practically an infusible, insoluble state.

Our density determinations on the various samples point to a probable error in the percentage composition data supplied to us. If one assumes the percentage values correct, then our data give little light on the electrical effect of the varnish. Each sample has been tested at various frequencies, but only those frequencies that are about equal will be shown here for comparison.

TABLE 45.—Possible Effect of Relative Per Cent of Varnish to Paper on Phase Difference

Per cent of varnish	Wave length (λ_m)	Frequency, cycles per second	Phase difference (ψ)
	Meters		Degrees
30	1335	224 700	2.83
40	1415	212 000	4.07
50	1340	223 900	2.56
55	1325	226 400	3.00
60	1305	229 900	2.05

A more complete understanding of the effect of composition on the electrical properties of such materials may be obtained when the testing is done under controlled atmospheric conditions.

By referring to the tabulated data (p. 588), one may see that, in general, most second-grade materials have lower phase difference than first-grade material. Materials of this grade average about 30 per cent varnish. In some cases there may also be a different base paper used in the second-grade material.

By second grade we mean here the following materials and grades:

Material	Grade
Bakelite-Dilecto	X
Bakelite Micarta	323 and 213
Formica	P

Formica, M–2, may be considered as second grade also, but is a different type of material and does not show the peculiarity cited above.

The above grades are not recommended by the manufacturers for use on radio apparatus. These grades have a distinct use as commercial insulators possessing better mechanical and, in some respects, better machining properties than the first-grade materials.

On Moisture Absorption.—What has been said above concerning the samples prepared for a study on phase difference may be said of the samples considered in the table below. It will be noticed that the percentage by weight of water absorbed by the various samples does not decrease as the percentage of varnish increases, neither does the density decrease as the percentage of varnish increases. The varnish should protect the cellulose fiber of the paper from the water in proportion to the degree of saturation of the cellulose fiber by the varnish. This assumes that the surfaces of the several samples are uniform, and that the size, thickness, and weight of the samples are about the same.

If the density of the paper is taken as 1.44 and of the varnish as 1.30, then the experimental value of density ($D = 1.40$) for the 30 per cent resin sample is about correct, but the percentage of moisture absorbed is low.

TABLE 46.—Effect of Percentage of Varnish Upon Percentage by Weight of Moisture Absorbed in 24 Hours

Percentage of varnish	Density	Percentage by weight of water absorbed in 24 hours	Size of sample
	g/cm^3		cm
30	1.40	0.17	5 by 10 by 0.64
40	1.35	.34	.....
50	1.39	1.13	.....
55	1.35	.18	.....
60	1.38	.34	.....

It will be noticed in the data on page 593 that the second-grade materials have a higher percentage of moisture absorption. In some cases the second-grade materials absorb 10 times as much water in 24 hours as the first grades. That is why only the first grades are recommended for the majority of radio work.

It is not to be understood that this type of material absorbs water, swells and becomes flexible as does vulcanized fiber. We have not made any moisture-absorption tests extending more than 24 hours.

On Mechanical Properties.—Theoretically if one considers only well-cured samples of laminated phenolic insulating materials, the sample with the higher percentage of varnish will have lower tensile and transverse strength, be harder, be more brittle, and be difficult to manipulate in some machining operations.

For reasons stated on page 617 we can not illustrate the theory by data on samples of different percentage of varnish, nor are we sufficiently sure that the samples we have hold closely enough to the percentage composition stated.

23. COMPARISON OF PROPERTIES OF HARD RUBBER, VULCANIZED FIBER, LAMINATED AND MOLDED PHENOLIC INSULATING MATERIALS

A comparative summary of the properties of these materials is tabulated below. This is based upon the results of many investigations and the experience of many users and manufacturers. Hard rubber and vulcanized fiber have been used by engineers for many years. Some still find in these materials the particular property needed for their work, others have felt a need for some other material but have not had sufficient information to choose that better material. Some engineers have failed to study these two materials—hard rubber and vulcanized fiber—sufficiently to use them wisely and economically. Often too little or too much has been expected of an insulating material.

The problem of the proper use of the proper insulating material has been at once facilitated and complicated by the advent of the laminated and molded phenolic materials. These materials lend themselves to many uses not satisfactorily filled by either hard-rubber or vulcanized fiber, but they are likewise used where hard rubber or fiber might better be used. The phenolic insulating materials are for many purposes not hard-rubber substitutes. They are distinctly different. It is evident that the idea of phenolic insulating materials as a hard-rubber substitute has been overworked. This tendency may well be explained on the ground that the phenolic insulating materials are really quite new and yet in a state of development. Engineers have turned to this new material but have found little data at hand to direct them in its use.

Hard rubber is composed of crude rubber, sulphur, and usually some mineral filling compound. As previously stated, the relatively high cost of crude rubber has induced some makers of hard rubber to use reclaimed rubber or else load the new rubber with a high percentage of mineral filler. The lack of a proper understanding of this fact between the maker and the user has often resulted in unjust censure of hard rubber as an insulator. The better grades of hard rubber are made of new rubber containing no mineral filler and are free from excess sulphur. With these points in mind it is evident that the values assigned to a particular property or the effect of a certain test must necessarily be broad. Neither the best nor the poorest grade of hard rubber is considered in the data and opinions given in the following table.

Vulcanized fiber is made of parchmentized paper. For the better grades of fiber rag base paper is used. The paper is run slowly through a warm concentrated solution of sulphuric acid or zinc chloride, the one solution being used in making fiber sheets one-eighth inch thick or less, the other solution being used for thicknesses greater than one-eighth inch. The purpose of the acid or zinc chloride is to soften the walls of the cellulose (cotton) fibers, so that when several sheets of treated paper are pressed together the fibers tend to mat and cohere. The treated paper is wound on a drum until the cylindrical tube of the desired thickness is obtained, the cylindrical tube being then cut so as to form a sheet whose width is equal to the width of the paper and whose length is equal to the circumference of the drum. The composite sheet of treated paper is then soaked in water to remove the acid or zinc chloride, dried, and pressed. The term "vulcanized" is somewhat misleading. Fiber does not depend upon heat and pressure to cure it as does hard rubber.

Vulcanized fiber varies much in both mechanical and electrical properties. The properties depend somewhat on the quality of rags used, the amount of residual sulphuric acid or zinc chloride, and upon the density of the finished product. Since the various processes of fiber making are difficult to control, the following statements relative to fiber must be taken as general and the recorded numerical data as average data.

The several makes and many grades of laminated phenolic insulating material have been discussed quite fully in this paper. It will be evident to the reader that any numerical value or statement given in the following summary table is an approximation.

The molded phenolic insulating materials are subject to as many variations as hard rubber. There is probably not as much variation in the phenolic resin binder in the molded phenolic materials as there is in the crude or reclaimed rubber binder of hard rubber. There are many other chances for variation in the press pressure and temperature, length of curing in the presses, and kind and quality of filler. Some of the fillers used are wood flour, pulverized mica, and asbestos. The kind and amount of filler will affect both the mechanical and electrical properties. All these possible variations make the data only approximate and require rather general statements in the summary table.

Most of the numerical data given in the table below are from tests made at the Bureau of Standards. Actual results on hard-rubber samples are given on page 622. The statements concerning the effects of various things on the different insulating materials are based on the experience of various members of the Bureau of Standards staff and upon the experience of the manufacturers of these materials. The manufacturers' experience on hard rubber and vulcanized fiber extends over many years, while the experience on the phenolic insulating materials is much more limited.

While it is possible to make up insulating materials which would give results different from those recorded for any particular property, yet it is believed that this table gives information in a condensed form which will serve to show some of the limitations as well as some of the possibilities of these various materials as now obtainable commercially.

TABLE 47.—Comparison of Properties of Hard Rubber, Vulcanized Fiber, Laminated and Molded Phenolic Insulating Materials

Properties	Hard rubber	Vulcanized fiber	Phenolic insulating materials	
			Laminated	Molded
Surface restivity at 50 per cent relative humidity, ohms	10^{12} to $>10^{15}$		10^{11}	10^{11}
Phase difference (ψ) at radio frequencies, degrees	0.5 [a]	3.0 to [b]	1.5 to 4.0	1.5 to 4.0
Dielectric constant (K) at radio frequencies	3.0 [a]	5.0 [b]	4.5 to 6.0	5.0 to 7.5
Dielectric strength...volts/mm	10 000 to 38 000 [c, d]	9 000 to 16 000 [c, d]	27 000 to 45 000 [c, d]	9 000 to 40 000 [c, d]
Tensile strength.....lbs./in.^{2}	3 500 to 6 500	9 000 to 20 000	10 000 to 25 000	3 500 to 7 000
Water absorbed in 24 hours, percentage by weight.	0.02	26 to 45 [e]	0.2 to 1.0 [f]	0.05 to 0.2[g]
Density.....g/cm^3	1.12 to 1.40 [h]	1.3 to 1.5	1.3 to 1.4	1.3 to 1.4
Thermal expansivity (at 20 to 60° C)	60 to 80×10^{-6}	27×10^{-6}	20 to 30×10^{-6}	25 to 45×10^{-6}
Effect of age	Deteriorates slowly, but if properly vulcanized and protected from the light it is not affected	Improves in quality by seasoning [i]	Improves [j]	No depreciation in physical or chemical properties; slight increase in hardness [j]
Heat	At 65.5° C (150° F) pure hard rubber softens perceptibly; at 100° C (212° F.) it is so soft it may be bent easily; at 115.5° C (240° F) it becomes leathery and may readily be cut with a knife; melts at 200° C (392° F) [c]	Will not melt under any circumstances; not readily inflammable; at very high temperature chars and becomes brittle; active combustion begins at about 343° C (650° F)	Not readily inflammable; will withstand continuously a temperature of 149° C (300° F); heat tends to complete the reaction and volatile substances are driven off. Hence, when cooled it shrinks considerably and may split; shrinks and loses in weight above 60° C [k]	See statement for laminated materials [l]
Sunlight	Discolors and disintegrates after a few months; the sulphur of the hard rubber is oxidized, forming the equivalent of sulphuric acid; this may take up ammonia from the air or may attack the filling materials forming the various sulphates upon the surface; the surface resistivity is greatly reduced [m]	No effect [c]	No visible effect [n]	After two and one-half years some materials show a slight change, such as discoloration or very fine cracks; other materials show no such change [c, n]
Effect of ultra-violet light for 20 hours	Discolors and disintegrates; the action is as pronounced for a few hours' exposure to ultra-violet light as for many months exposure to sunlight; the surface resistivity is greatly reduced [m]	No data	Appreciable lowering of surface resistivity	Appreciable lowering of surface resistivity [m]

Moist air	Hard-rubber compounds excepting those containing organic substances other than rubber are practically moisture proof	Absorbs water freely, but without permanent injury; while saturated it becomes soft and flexible and swells; warps and twists upon drying	Absorbs slight amount of water, reducing dielectric properties [o]	Absorbs slight amount of water, reducing dielectric properties
Steam	The only effect is that due to the high temperature	Same as above, except absorption is more rapid	Best grades not affected beyond slight absorption of moisture; after a few days in steam the cheaper grades will swell appreciably and split; superheated steam tends to warp and blister all grades of the material	Absorbs a slight amount of moisture; if steam is superheated, the high temperature will cause decomposition
Solvents:				
Acetone	Attacks, dissolving oils and free sulphur [c]	No permanent effect [c]	No effect [c,p]	No effect [c,p]
Alcohol	Attacks to a slight degree [c]	do.[c]	do.[c,p]	Do. [c,p]
Ammonia	No effect [c]	do.[c]	Strong solutions may cause material to swell [c]	No effect other than slight absorption of moisture [c]
Analine	Softens it at ordinary temperature [c]	Not known	Probably no effect [c]	Probably no effect [c]
Benzol	do.[c]	No permanent effect [c]	do.[c,p]	Do.[c,p]
Carbon bisulphide	Dissolves small amount of hard rubber and any free sulphur [c]	do.[c]	do.[c,p]	Do.[c,p]
Ether	do. [c]	do.[c]	No effect [c]	Do.[c,p]

[a] These values were obtained at frequencies between 750 000 and 75 000 cycles per second (400 to 4000 meters wave length), there being very little change throughout this range. The grade of the sample tested is unknown, so values differing somewhat from these might be expected on other samples using different quantities and kinds of filler.

[b] Values of ψ and K may be somewhat lower or much higher, depending on amount of moisture present in the fiber.

[c] Information obtained from sources other than the Bureau of Standards.

[d] Values vary with the thickness of sample, kind of filler, shape of electrodes used, rate of increase of voltage, as well as atmospheric conditions under which tests are made.

[e] The Railway Signal Association specifications require an absorption when immersed in water at 70° F for 24 hours, not to exceed 45 per cent by weight for one-eighth inch fiber, 30 per cent for three-sixteenth inch fiber, and 26 per cent for one-fourth inch fiber.

[f] Dependent upon nature of surface, surface area, and kind and amount of filler.

[g] Varies with polish of mold, press pressure, and temperature, length of curing, ratio of resin to filler, kind of filler, and size of sample.

[h] The density depends on the amount of sulphur present and increases with the increase in amount of filler. Pure hard rubber ranges from 1.12 to 1.25. A fair commercial quality ranges from 1.25 to 1.40.

[i] This means seasoning or aging in a protected place, such as a storage house.

[j] These materials are of comparatively recent development, and hence no information has been gained covering very long periods. Theoretically, under certain conditions the chemical reactions would tend to continue, which would age and improve the material. One manufacturer claims a slight improvement in dielectric properties and a marked improvement in machining qualities when the aging takes place under ordinary atmospheric and temperature conditions. If the aging takes place in a moist atmosphere, the dielectric properties are subject to deterioration.

[k] See pages 580 to 583 and 187 of this paper.

[l] When subjected to temperatures above 60° C (140° F) some of the volatile matter is driven off, resulting in the shrinking and loss in weight of the material. This can be carried out many times with the same result, the material becoming more brittle. Tests made on these materials show that they are very erratic in behavior and do not expand or contract in a uniform way. It seems altogether probable that a point would be reached after all volatile matters had been driven off, when further subjection to a moderate temperature and subsequent cooling would not result in further shrinkage. This has not been proved experimentally. High temperature will produce decomposition. Further information regarding these tests will be found in Scientific Paper of the Bureau of Standards No. 352. (See also pages 580 to 583 and 187 of this paper.)

[m] A further discussion of the tests at the Bureau of Standards may be found in Scientific Paper of the Bureau of Standards, No. 234.

[n] See effect of ultra-violet light.

[o] See discussion on pages 599 and 600 of this paper.

[p] Strong solvents affect the phenolic binder of the material to a limited extent unless the chemical reaction has been carried to the point where it is in the insoluble state. This condition would render the sheet material too brittle for general use. When water is present, the material will absorb it in various amounts.

TABLE 47.—Comparison of Properties of Hard Rubber, Vulcanized Fiber, Laminated and Molded Phenolic Insulating Materials—Continued

Properties	Hard rubber	Vulcanized fiber	Phenolic insulating materials	
			Laminated	Molded
Solvents—Continued.				
Naphtha	Softens and swells to slight extent [c]	No permanent effect [c]	Probably no effect [c]	Probably no effect [c, p]
Oil of turpentine	Dissolves in boiling oil [c]	do.[c]	do.[c]	Do.[c, p]
Oil:				
Mineral	Slight softening [c]	Slight absorption [c]	Practically impervious [c]	Practically impervious [c]
Organic	Unaffected [c]	do.[c]	do.[c]	Do.[c]
Effect of weak acids	do	Swells due to absorbed water; may be attacked after some time [c]	Practically unaffected except for absorption of water [q]	Practically unaffected [r]
Weak caustic alkalis	do	do.[c]	Does not successfully resist the action of alkali unless very dilute	Does not successfully resist the action of alkali unless very dilute
Stronger acids (HNO_3, HCl, H_2SO_4)	Not attacked by concentrated hydrochloric, hydrofluoric, acetic acids; not attacked by sulphuric acid of less than 1.50 specific gravity or nitric acid of less than 1.12 specific gravity [c]	Cellulose fiber attacked soon decomposes	Decomposes; rapidity depends on specific gravity and temperature of acid	Decomposes; rapidity depends on specific gravity and temperature of acid [s]
Stronger caustic alkalis	No effect	do	Binder and filler decompose [r]	Completely destroy; speed of the reaction depends on the strength of the solution
Ozone	Oxidizes and soon ruins it for electrical purposes	No effect [c]	Not known	Not known
Metallic inserts	Rapidly deteriorated by contact with iron or copper, the metals themselves being corroded; the inserts should be coated with tin, paper, unvulcanized rubber, or other mutually protecting medium	do	No effect	No effect
Machining qualities	Admits of a high polish; machines less accurately than would be supposed, due to great resiliency; the better the grade the more readily it is machined; quality may be judged roughly by color and texture, toughness, color, and grain of a shaving; has tendency to warp; can be molded but not accurately to size	Admits of a fine finish; may be sawed, punched, drilled, stamped, embossed, turned, planed, bent, tapped; tough, resists shock; can not be molded [t]	Admits of a good polish; can be sawed, punched, drilled, stamped, turned, planed, knurled, embossed, milled, tapped either with or against the grain, though not as easily as hard rubber and vulcanized fiber; tough, resists shock; can not be molded [t]	Admits of a fine lasting polish; can be machined, cut, filed, sawed with difficulty; can be molded accurately to size; quite brittle

Cost	About $2 per pound in sheet form	50–80 cents per pound up to 1 inch in thickness; about $5 per pound for 2 inches in thickness	About $1 per pound	Cost varies with complexity of steel molds

c Information obtained from sources other than the Bureau of Standards.

p Strong solvents affect the phenolic binder of the material to a limited extent unless the chemical reaction has been carried to the point where it is in the insoluable state. This condition would render the sheet material too brittle for general use. When water is present, the material will absorb it in various amounts.

q The effects vary with the materials, different molding mixtures, and acids. Nitric acid is harmful. In general weak acids will mar the surface and attack the edge of a sample soon after it comes in contact with the sample, but there is little or no further change.

r See page 608 of this paper.

s The action differs for various materials and grades. Some materials resist the action of a 30 per cent solution of H_2SO_4 for several months and will withstand hydrochloric acid without any visible sign of attack. On other materials of this class sulphuric and nitric acids attack the surface of the sample and form a protective coating. This ruins the sample as far as further electrical use is concerned, but on removing the sample from the acid and cutting it open it is found that the acid has not penetrated more than one-sixteenth inch after several months' exposure to the acid.

t Thin sheets can be pressed to simple shapes when warm.

VI. SUMMARY

A comprehensive experimental research has been made upon the principal electrical and mechanical and a few other properties of the laminated phenolic materials. The measurements were made upon the sheets of materials as furnished commercially. Specimens for measurement of all the various properties were cut from the same large sheet, so the results are comparable. The influences of a large number of factors upon the properties were studied and have been discussed herein. The scope of the work may be judged from the table of contents. The properties varied greatly with the thickness of sheet as well as grade of material. While there were, furthermore, considerable variations from sample to sample, characteristic values of the properties are given by the summary table below. This table gives the averages of all data on samples received at the Bureau of Standards between December 20, 1917, and August 24, 1919.

TABLE 48.—General Summary of Properties

Property	Bakelite-Dilecto, grade—			Bakelite Micarta, grade—		
	XX	X	Continental Bakelite	32-X and 21-X	323 and 213	21-D
Phase difference ..... degrees	2.1	1.9	3.8	2.9	2.4	5.6
Power factor ..... per cent	3.6	3.3	6.6	5.1	4.2	9.9
Dielectric constant	5.2	5.5	5.3	5.8	5.9	6.4
Flash-over voltage, radio frequency	19 800	19 800	21 100	20 000	19 700	22 000
Volume resistivity ..... ohm-cm $\times 10^9$	18 800	520 000	200	9 400	29 900	100
Surface resistivity at 24 per cent humidity	38 900	445 000	100	3 300	10 400	580
Surface resistivity at 50 per cent humidity	3 900	4 000	9	900	2 700	130
Surface resistivity at 84 per cent humidity	48	6	1	22	30	3
Density	1.34	1.34	1.30	1.35	1.37	1.36
Water absorbed in 24 hours ..... per cent	.21	1.76	.49	.33	.88	.91
Ultimate tensile strength ..... lbs./in.^{2}	12 800	17 800	8 700	10 900	16 600	8 900
Modulus of (tensile) elasticity ..... 1000 lbs./in.^{2}	1 500	2 100	.....	.....	.....	.....
Modulus of (transverse) rupture ..... lbs./in.^{2}	18 000	22 700	13 600	16 200	21 400	13 900
Modulus of (transverse) elasticity ..... 1000 lbs./in.^{2}	1 310	1 900	.....	1 260	1 600	.....
Brinell hardness at 20–30° C	41	28	32	39	34	37
Brinell hardness at 50° C	40	26	30	34	32	32
Scleroscope hardness at 20–30° C	88	68	58	83	81	75
Scleroscope hardness at 50° C	83	64	58	80	76	70
Impact strength ..... ft.-lb	0.7	0.9	1.2	0.2	0.8	2.1

TABLE 48.—General Summary of Properties—Continued.

Property	Condensite Celoron, grade—		Formica, grade—			
	10 and 15	20	M	M-2	P	R
Phase difference.....degrees..	2.9	6.3	3.0	3.7	2.9	4.5
Power factor.....per cent..	5.1	11.0	5.3	7.7	5.1	7.9
Dielectric constant.....	6.6	6.8	5.6	5.8	5.8	6.5
Flash-over voltage, radio frequency.....	21 000	27 800	19 700	20 600	18 300	21 000
Volume resistivity.....ohm-cm×10^8..	15 100	63	2 200	250	900	60
Surface resistivity at 24 per cent humidity.....	12 500	1 800	600	340	670	340
Surface resistivity at 50 per cent humidity.....	2 300	275	160	120	300	220
Surface resistivity at 84 per cent humidity.....	77	13	10	5	34	80
Density.....	1.41	1.34	1.36	1.34	1.38	1.38
Water absorbed in 24 hours.....per cent..	.26	.39	.26	.49	.60	1.22
Ultimate tensile strength.....lbs./in.^{2}..	12 300	7 800	12 600	13 200	18 200	9 900
Modulus of (tensile) elasticity.....1000 lbs./in.^{2}..	.....	.....	.....	1 950	2 260	.....
Modulus of (transverse) rupture.....lbs./in.^{2}..	15 800	11 100	17 700	17 300	21 400	15 100
Modulus of (transverse) elasticity.....1000 lbs./in.^{2}..	.....	.....	1 270	1 430	1 410	.....
Brinell hardness at 20–30° C.....	38	38	36	44	38	39
Brinell hardness at 50° C.....	35	32	34	41	34	34
Scleroscope hardness at 20–30° C.....	86	87	84	90	86	70
Scleroscope hardness at 50° C.....	82	82	80	89	82	64
Impact strength.....ft.-lb..	0.4	1.0	0.3	0.3	1.5	2.9

WASHINGTON, November 30, 1921

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PHOTOMICROGRAPHY OF PAPER FIBERS

BY

R. E. LOFTON, Associate Physicist

Bureau of Standards

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PHOTOMICROGRAPHY OF PAPER FIBERS.

By R. E. Lofton.

ABSTRACT.

This paper describes some of the more important factors in the photomicrography of vegetable fibers, especially of those used in the paper industry. As regards illumination it is shown that the carbon arc can be advantageously replaced by an incandescent stereoptican lamp. Different types of objectives are discussed, and it is shown that the working qualities of most objectives may be greatly improved by the use of proper light filters. Three types of light filters, with general directions for preparing them, are discussed, and directions are given for determining the quality of light transmitted by filters. The purpose and proper use of the substage condenser and diaphragm are discussed. It is shown that, where an object lying in different planes is to be photographed, an objective of comparatively long focal length will give better results than one of shorter focal length, and that this arrangement requires a longer bellows extension. Other advantages of a long bellows extension are also described. Different types of photographic plates are described and suggestions as to the best type of plate to use for photomicrographic work are given. Suggestions for staining and preparing the material to be photographed are included, as well as some suggestions as to the value of photographs for permanent records and in the study and control of materials and mill processes. A short bibliography on photomicrography and related subjects is given.

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I. PURPOSE OF PUBLICATION.

The purpose of this paper is to put before those who desire to take up the microscopic and photomicrographic study of the vegetable fibers used in paper-making some essentials which are often overlooked, but without which the full measure of success in this field can not be had. Investigations of the value of stains, of light filters, of a long bellows camera as against one of shorter bellows, etc., have demonstrated that these factors are really

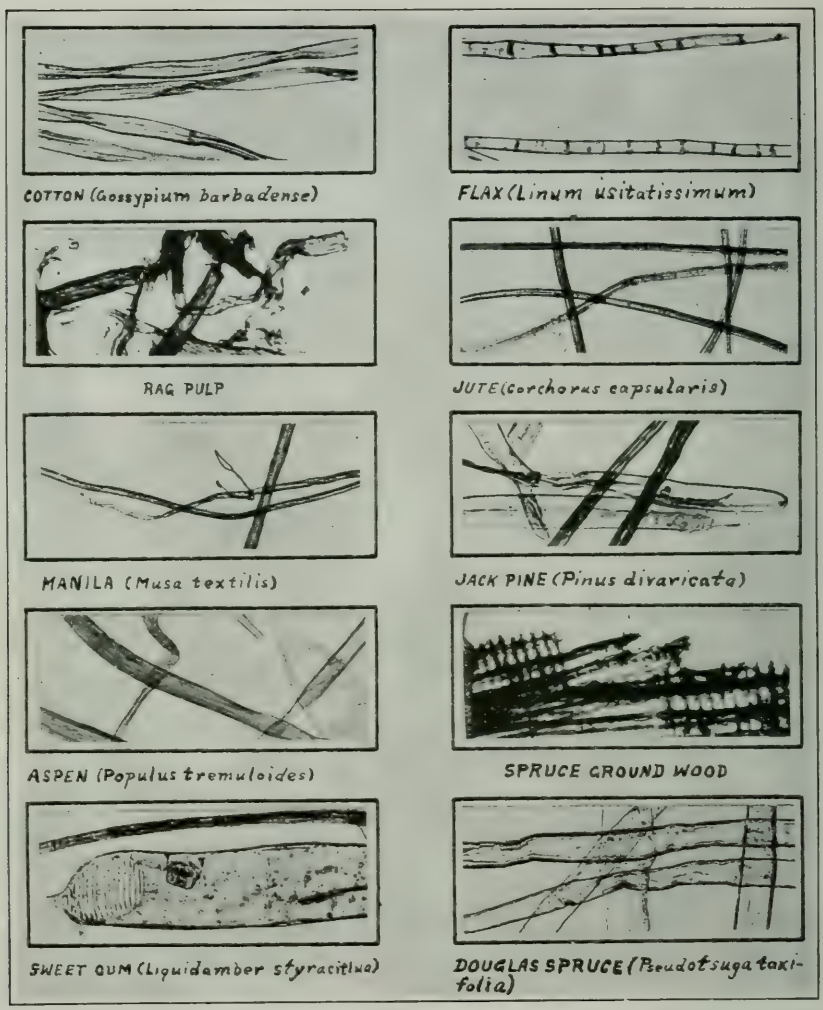


FIG. 1.—*Photomicrographs of some common paper fibers.* ×100.

All vegetable fibers are fairly translucent and have central canals. Cotton is a seed hair, ribbon-like, often twisted, blunt ends, length 10–55 mm. Manila is a leaf-stalk fiber, round, gradually tapering ends, length 3–12 mm. Flax and jute are bast fibers, cylindrical, gradually tapering ends. Flax has prominent cross markings, often x-shaped. Jute has fine longitudinal lines. Length: Flax, 4–66 mm; jute, 1–5 mm. Wood fibers come from the trunk and larger branches of trees. Aspen and sweet gum are broadleaf trees; fibers are cylindrical, tapering ends. Broad-leaf woods are characterized by comparatively large tubular vessels having numerous pores and sometimes bars across either end. Length of broad-leaf fibers: 0.5–2.5 mm. Jack pine and Douglas spruce are coniferous trees, fibers ribbon-like, blunt or rounded ends, much broader than cotton, and have frequent pores. Length coniferous fibers, 1.5–6.0 mm. Ground wood is characterized by frequent bundles of fibers showing very distinct cross cells, by broken and mutilated fibers, and by extreme variation in size of particles.

essential in the microscopy and especially the photomicroscopy of fibrous materials.

Equally essential, however, is a thorough familiarity with the laws and properties of light and lenses, with the proper use of the microscope and the functions of its various parts, and with the nature and properties of developers and the photographic plate. It is beyond the scope of this paper to discuss all these subjects, and persons feeling the need of additional information will find them discussed and treated in detail in the various books and publications which are available to all.[1]

What is said herein regarding fibers used in paper-making will apply equally well to all fibrous materials, textile as well as paper, animal as well as vegetable fibers.

II. SOURCE OF ILLUMINATION.

In the beginning of these experiments a small incandescent hand-feed arc lamp was used, but the variation in intensity of illumination and the frequent adjustment of the feeding mechanism required by this light, with the consequent periodic diversion of the worker's attention, soon led to the attempt to find a substitute. The use of an incandescent light instead of a carbon arc has the additional advantage that a source of heat which has often injured or destroyed valuable equipment and delicate objects being photographed is eliminated. After some experimenting, a 300-watt Mazda stereoptican lamp with tubular bulb was substituted for the carbon arc and found to be satisfactory. Photographs at a magnification of 1000 diameters, using a Seed 23 plate and a deep blue filter, were made at a 10-minute exposure with this lamp. Finally, a new 400-watt Mazda stereoptican lamp, recently put on the market, was substituted for the 300-watt lamp. This new lamp is much to be preferred to the 300-watt, as the six filaments furnishing the light lie in a vertical plane, and may thus be turned either edgewise to the object, giving an effect similar to that of the Nernst glower, for high magnifications, or may be turned flatwise so as to illuminate a larger field for low power photomicrography.

III. LIGHT FILTERS.

A study of the properties of light and of optical instruments will convince the reader, if he has not already been convinced, that all optical instruments have their limitations. The best that science

[1] See short bibliography at end of this publication.

and art can do in the construction of achromatic objectives with the different varieties of optical glass available at present is to make a perfect correction for two colors of the spectrum, called the "preferred" or "chosen" colors. These chosen colors are brought to a point focus nearer the objective than are the other colors, which are focused at various points along the axis of the objective. (See Fig. 2.) The colors chosen for visual work are yellow and green, usually spoken of as "yellow-green," or "applegreen," because the normal human eye is most sensitive to this portion of the spectrum. Since the ordinary photographic plate is not at all sensitive to yellow-green light, but is most sensitive to the blue-violet region of the spectrum, objectives intended exclusively for photographic use are corrected for blue light. (See Fig. 3.) As photographic objectives of 16 mm equivalent focus are comparatively rare, however, almost all photomicrographic work is done with achromatic outfits constructed for visual work, unless, perchance, an apochromatic outfit is at hand.

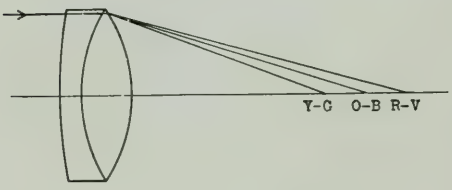


FIG. 2.—*Shows objective corrected for visual use.*

Yellow-green is the "chosen color" (See text for explanation).

It is evident then, since the visual focus and the photographic or chemical focus are not the same (see Fig. 4), that best results can not be expected if white light is used in conjunction with an achromatic outfit, since white light is composed of all the colors of the spectrum. Those who attempt to make photomicrographs by using an achromatic outfit and white light are faced at once with the problem as to how to make the visual and the chemical foci the same. If a good dry plate, sensitive to yellow-green only, were on the market, it would afford the most desirable solution of the problem; for a microscope objective is supposed to give the best results, other things being equal, when transmitting only those colors of the spectrum for which it is corrected. Since such a photographic plate is not to be had at the present time,

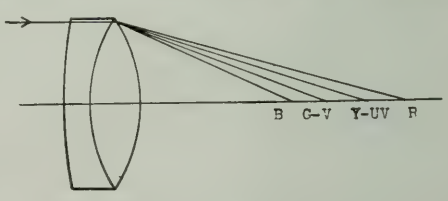


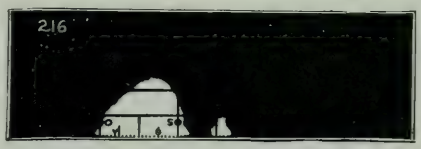
FIG. 3.—*Shows objective corrected for photographic use.*

Blue is the "chosen color" (See text for explanation).

however, the only alternative left is the use of ray or light filters, whose function it is to absorb all those rays of the spectrum not desirable for illuminating the object to be photographed.

Light filters may be purchased, or may be made in the photographic workroom which will transmit any portion of the spectrum, usually within rather broad limits, however. A filter should be chosen which will transmit only a very narrow band of the color of the spectrum to be used; that is, the light transmitted should be as nearly monochromatic as possible. Unfortunately, however, filters transmitting a very narrow band do not usually transmit a large percentage of the incident light.

Spectrogram of Ordinary Plate.



Spectrogram of Orthocromatic Plate.

Spectrogram of Pancromatic Plate.

FIG. 4

The letters at the bottom of each spectrogram refer to the color of the light falling on the plate; UV, ultraviolet; V, violet; B, blue; G, green; Y, yellow; O, orange; and R, red. The numbers give the wave length of the light in millionths of a millimeter.

Three different types of filters are in common use: (1) Liquid filters, made by dissolving various dyes, depending on the color of the light wanted, in their proper solvents; (2) filters made from colored glass; and (3) filters made by staining transparent films in various dye solutions.

Liquid filters have the disadvantages that they are usually not constant for any length of time in the quality and quantity of light they transmit, that the liquid of which they are composed frequently gets spilled or leaks out over the apparatus and thus sometimes causes great injury, and that they require considerable time and care to keep in proper working condition.

Quite a number of filters made from colored films are on the market and some of them are good. There are also available glasses of various colors which make excellent filters when ground and polished properly. Neither the use of colored films, mounted on or between glass, nor that of glass filters has the disadvantages attending the use of liquid filters.

A suitable filter, often superior to most available, can be made by treating an ordinary photographic plate in a plain fixing bath

in the dark room until all the silver salts are removed, washing, and then immersing in an aqueous or aqueous-alcoholic solution of a suitable dye for a few hours.

Although photographic plates may be had sensitive to all colors, there are various advantages in using only the shorter wave lengths of light, particularly blue light. All plates are more sensitive to blue and blue-violet light than to other colors, and so when exposed to light of this color require a shorter time of exposure. (See Fig. 4.) The use of filters transmitting only the shorter wave lengths also has the advantage of increasing the resolving power of the objective. The theoretical resolving power, R, of a lens—that is, the minimum distance apart of two or more dots or lines at which the lens can form a distinct image of each dot or line—is given by the formula

$$R = \frac{\lambda}{2\ \text{N. A.}}$$

where λ is the wave length of the light used and N. A. is the numerical aperture of the lens.

By the use of light filters greater contrast is had between the material to be photographed and the background, so that it is possible in this way, especially with the use of stains as suggested below, to have the printed image stand out in bold relief with no background whatever showing. If a blue filter is being used, the greatest contrast between the background and the printed image is obtained by staining the material to be photographed with red or yellow dyes. Black dyes are suitable of course with any light, provided the fibers do not take them up in such quantity as to prevent all detail of structure from showing. Dense staining must be avoided in all cases, sometimes a mere tinting being sufficient.

If one is to get the best results with light filters, there must be some practical method for determining the quality of light being transmitted by the filter used, since this can not be done by the unaided eye. The most convenient means of determining the transmission of light filters is a replica transmission grating of about 1 by 2 inches in size, having 5000 or 6000 lines per inch. To examine the quality of light transmitted by a given filter by this means, all light must be excluded from the grating except that passing through the filter. The grating must be held between the light filter and the eye, and the eye and grating directed somewhat to one side and not directly toward the light filter. The

various colors of the light transmitted can then be seen and the quality of the filter determined.

Another solution of the problem of making the chemical and visual foci identical is the employment of an apochromatic objective and compensating ocular. If one wishes to use the objective without an ocular, however, a monochromatic filter should be used, as the apochromat is intentionally so constructed that, when white light is used, it will not give an image free from color except in combination with a compensating ocular. Notwithstanding the finer corrections of the apochromats, it is doubtful if their performance in photomicrography is much superior to that of the best achromats when used under the most favorable conditions. Besides being less expensive, the achromats have the advantage of giving a flatter image, that is, one having less curvature.

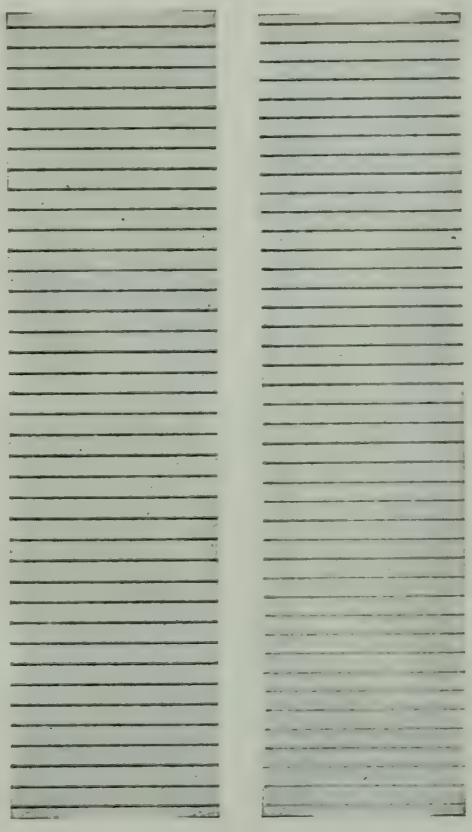


FIG. 5. FIG. 6.

Figs. 5 and 6. The left half of photomicrographs at a magnification of 250-times of a scale ruled on glass, show the relative flatness of image given by a 16 mm achromatic objective (Fig. 5) and by a 16 mm apochromatic objective (Fig. 6).

Figures 5 and 6, which are photomicrographs at a magnification of 250 diameters of a scale ruled on a glass slide, show something of the relative merits of an achromatic objective and an apochromatic objective in giving flatness of image. Figure 5, the scale as photographed with the achromatic objective, shows that this objective gives a slighter flatter image than the apochromatic objective, with which the same scale was photographed, as shown in Figure 6. Both objectives have an equivalent focus of 16 mm.

IV. USE OF CONDENSERS.

For shorter focal lengths than 8 mm a regular substage condenser is not desirable, as better results are to be had by a condenser arrangement which will send a parallel or nearly parallel beam of light into the objective. This may be had by removing the regular substage condenser and placing at the proper point in the beam of light from the large condenser either a converging or a diverging lens of short focal length and relatively small diameter. The converging lens must be placed slightly outside the point, depending on its focal length, at which the rays are focused by the large condenser (see Fig. 7); the diverging lens, on the contrary, must be placed slightly within this point. (See Fig. 8.) This adjustment is easily carried out in a darkened room whose atmosphere contains floating particles of dust or smoke, as the path of the light rays can then be distinctly seen.

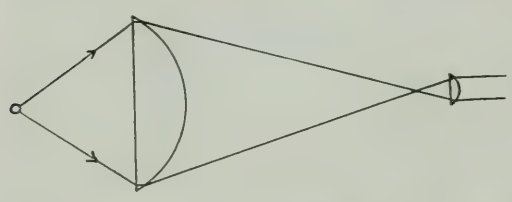


FIG. 7.—*Condenser arrangement with two converging lenses.*

V. USE OF SUBSTAGE DIAPHRAGM.

It is a fact well known to all photographers that to close down the diaphragm of the camera in making a photograph increases the depth of focus or penetrating power of the lens. The only disadvantage the ordinary photographer encounters in decreasing the diameter of the diaphragm is an increase in the time of exposure. In closing the substage diaphragm, however, the photomicrographer encounters an additional and far greater evil, namely, the appearance of diffraction or false images which mar the definition and perfection of the real image produced by the objective. Diffraction effects are most readily produced in using objectives of short focal length, but may be produced with comparatively long

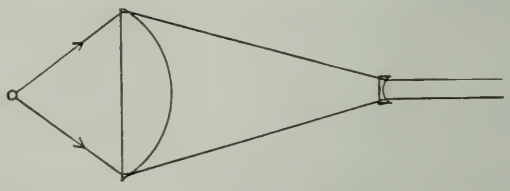


FIG. 8.—*Condenser arrangement with converging and diverging lenses.*

focal lengths if the diaphragm opening is made quite small. The purpose of the substage diaphragm is to exclude all those rays of light, from whatever source, which do not assist in forming the most perfect image of which the lens system is capable. Experience will soon teach one that the best results are not to be had when the diaphragm is wide open, and that the less the numerical

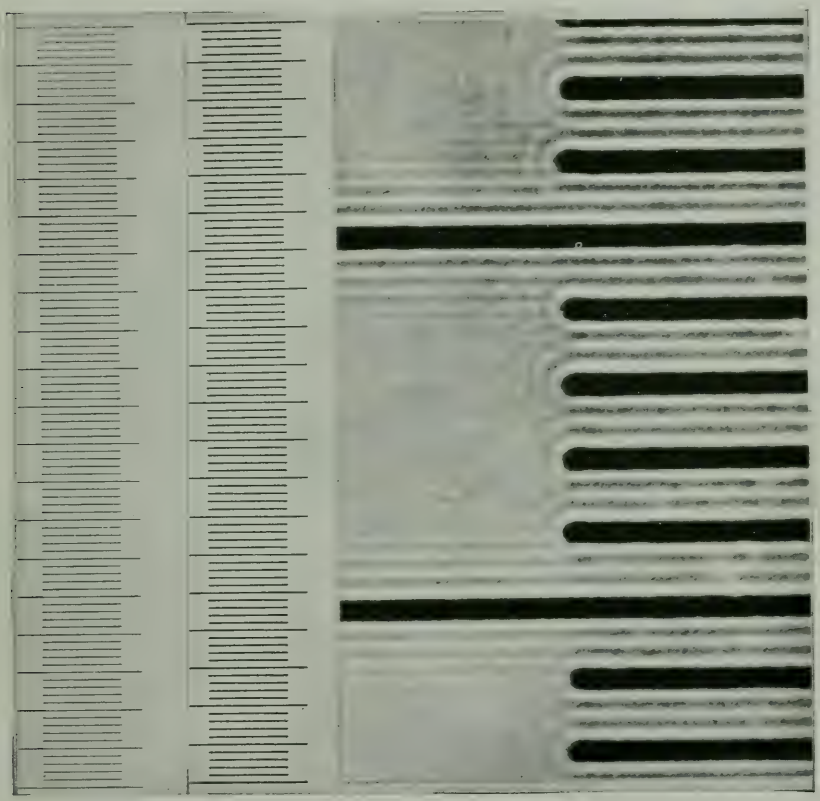


FIG. 9. FIG. 10. FIG 11.

Figs. 9, 10, and 11. Photomicrographs at a magnification of 100 times of a scale ruled on glass, show diffraction effects due to the use of substage diaphragm of too small aperture. The diaphragm openings were 14 mm, 4 mm, and 1 mm, respectively. Fig. 11 was subsequently enlarged 10 times to show more distinctly the effects of diffraction. All photographs were made with an achromatic objective of 16 mm focus and numerical aperture of 0.25.

aperture of the objective the smaller the diaphragm opening must be for the best definition. It has been found that best results are obtained with most objectives if the diaphragm is closed down until only about three-fourths or three-fifths of the back lens of the objective is lighted. The portion of the back lens which is lighted can be readily determined, if the mirror is properly adjusted, by removing the ocular and looking down into the tube

of the microscope. If the diaphragm opening is too large some of the rays of light enter at too great an angle with the axis of the optical system; when the diaphragm is much too large a large proportion of the rays enter so obliquely that there is produced what is called "flooding" of the objective with light, with the result that definition is almost or wholly destroyed. This latter condition exists, however, only with substage condensers of relatively large numerical aperture.

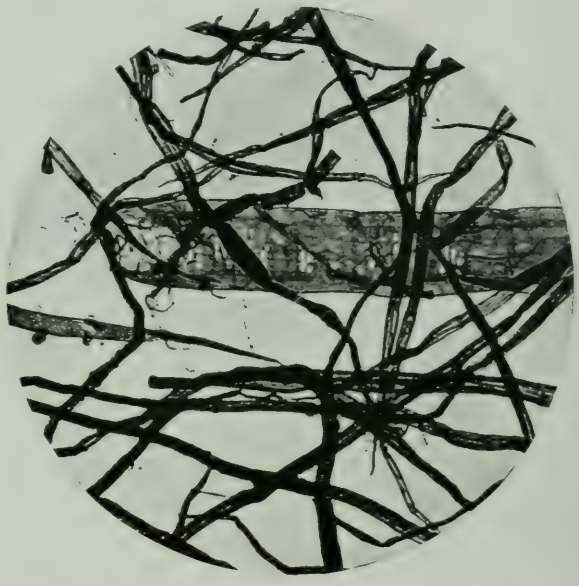


FIG. 11a.—*Chemical pulp from aspen×100.*

Stain	Bismarck brown
Mounting medium	Venetian turpentine
Objective	16 mm achromatic N. A. /0.25
Diaphragm	1 mm
Exposure	30 minutes

Notice the diffraction bands—black and white lines parallel with the outlines of the fibers. "Flare pots," caused by dust particles being brought partially into focus by the aid of the small diaphragm, are evident. Compare with Fig. 11 and Fig. 17.

Figures 9, 10, 11, and 11a illustrate these facts. In Figure 9 the substage diaphragm was full open, in 10 it was closed to 4 mm diameter, and in 11 and 11a[2] it was closed as far as possible,

[2] The filter used was made in the laboratory from a photographic plate and a blue dye, by the method outlined in this paper. This filter transmits a rather narrow band in the blue and violet, and a small and relatively weak band in the deep red. Instead of the regular substage condenser, an achromatic lens of 50 mm focal length was substituted and used throughout these experiments. In all photographs Seed No. 23 plates were used. Metol-hydroquinone developer of about double the usual strength was used for developing the plates. The same kind of developer of the usual strength was used in making the prints. All prints were made on regular glossy velox, and were rolled down on ferrotype plates to dry. The Venetian turpentine used as the mounting medium was an artificial product. An attempt was made to secure some true Venetian turpentine, but without success. The artificial product, however, gave excellent results, although sufficient time has not elapsed since it was first used here to indicate anything as to its value as a permanent mounting medium. The turpentine as used had a refractive index of 1.520 at 20° C.

to 1 mm. The sharpness of definition of Figure 9 is much better than that of 10; the lines in the latter are appreciably broader because of diffraction. In Figures 11 and 11a diffraction effects are more apparent. Figure 11 is a 10-times enlargement of the original photomicrograph made at a magnification of 100 diameters.

VI. CHOICE OF CAMERA AND OBJECTIVE.

Successful photomicrographs can not be made with a camera provided with a very short bellows, especially if a comparatively large photograph, an 8-inch by 10-inch, for example, is wanted at considerable magnification. If a short bellows is used, an objective of shorter focal length must be used than if the bellows were longer, and an objective of short focal length is never desirable if one of longer focal length will give the detail required in the photograph. The objective of long focal length has the following advantages over one of less focal length: (1) Greater depth of focus (2) gives a flatter image, and (3) shows a larger field. By depth of focus, sometimes called penetrating power, is meant the capacity of a lens to bring to a sharp focus at the same time an object, or objects, lying in slightly separated planes perpendicular to the axis of the lens. The depth of focus of a lens is directly proportional to the square of its equivalent focus, or focal length, and inversely proportional to its numerical aperture. A study of Figures 12, 13, and 14 will show that the greater the angle a which the peripheral rays make it crossing at the focusing point the less will be the depth of focus. Figures 12 and 13 represent lenses of the same focal length, but the diameter of 13 is much greater than that of 12, and it is very evident that the depth of focus of 13 is much less than that of 12. Figures 12 and 14 represent lenses of the same diameter, but 14 has a much shorter focal distance than 12, so that the peripheral rays through 14 make a greater angle than through 12; hence the depth of focus of 14 is less than that of 12. By the use of the diaphragm in

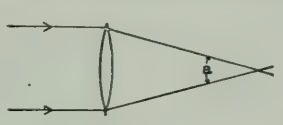


Fig. 12

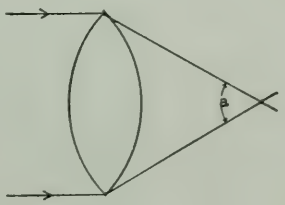


Fig 13

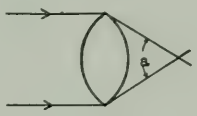


Fig 14

Figs. 12, 13 and 14. Variation in depth of focus with lenses of different equivalent focus and different numerical aperture. a = the angle which the marginal rays make in crossing at the principal focus.

photography the peripheral or marginal rays may be "stopped" out, thus decreasing the *effective* diameter of the lens, so that objects both relatively near to and relatively distant from the lens are in sharp focus.

Figures 15, 16, 17, and 18 illustrate the increasing depth of focus of objectives of increasing focal lengths.

It is shown in treatises on light that all points of real images formed by convergent lenses do not lie in the same plane, even though the optician may have exhausted his skill in making the

FIG. 15.—*Chemical pulp from aspen* ×100.

Stain	Bismarck brown
Mounting medium	Venetian turpentine
Objective	4 mm achromatic N. A. /0.85
Diaphragm	4 mm
Exposure	4 minutes

necessary corrections. Although this curvature of image is usually not evident in lenses of comparatively long focal length, it is quite evident in lenses of such short focal lengths as high power, or even moderately high power, microscope objectives. When rays parallel to the axis are incident at all points on the surface of the lens, those rays passing through the margin are brought to a focus at points nearer the lens than are those passing through nearer its center. Also, of the oblique rays passing through the center of the lens those making the greatest angle with the axis are brought to the focus nearest the lens. For these reasons the image *I* of

FIG. 16.—*Chemical pulp from aspen* ×100.

Stain	Bismarck brown
Mounting medium	Venetian turpentine
Objective	8 mm achromatic N. A. /0.50
Diaphragm	4 mm
Exposure	4 minutes

FIG. 17.—*Chemical pulp from aspen* ×100.

Stain	Bismarck brown
Mounting medium	Venetian turpentine
Objective	16 mm achromatic N. A. /0.25
Diaphragm	4 mm
Exposure	4 minutes

the object *O* will take the form as shown in Figure 19. Persons using the microscope have observed this condition, in that to get objects lying near the margin of the field of view in focus after the center of the field has been sharply focused upon one has to rack the objective slightly toward the object. In objectives of longer

FIG. 18.—*Chemical pulp from aspen* ×100.

Stain	Bismarck brown
Mounting medium	Venetian turpentine
Objective	48 mm achromatic N. A. /0.08
Diaphragm	4 mm
Exposure	4 minutes

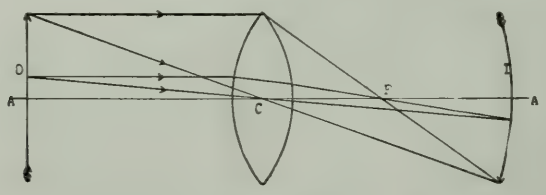


FIG. 19.—*Curvature of image of a convex lens.*

O=object; *I*=image; *C*=optical center of lens; *AA*=axis of lens; *F*=principal focus of lens. (See text for explanation)

focal length this curvature of image does not exist to such an extent, so that it is particularly advisable to use objectives of longer equivalent focus in photomicrography if a comparatively large photograph is to be made. But an objective of longer equivalent focus will require a longer bellows unless an eyepiece of higher

power be used, which is usually not desirable, since high-power eyepieces often unduly aggravate faults already existent, or even introduce new ones. Although compensating eyepieces must be used with apochromatic objectives unless monochromatic light is used, the use of eyepieces is not necessary with achromatic objectives, and not even desirable in most cases, if means are at hand

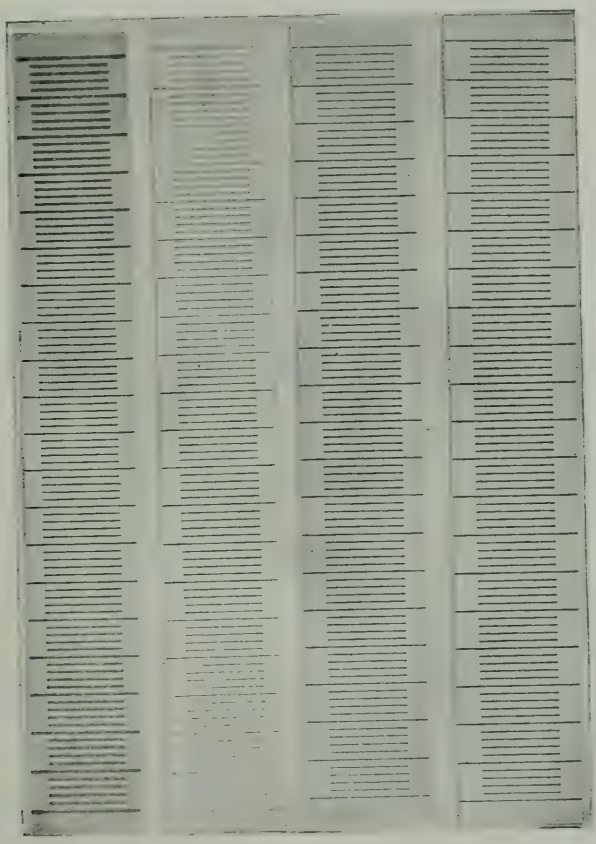


FIG. 20. FIG. 21. FIG. 22. FIG. 23.

Figs. 20, 21, 22, and 23, photomicrographs at a magnification of 100 times of a scale ruled on glass, show the greater flatness of image given by objectives of greater focal length. Fig. 20 was made with a 4 mm achromatic objective, Fig. 21 with an 8 mm achromatic objective, Fig. 22 with a 16 mm achromatic objective and Fig. 23 with a 48 mm achromatic objective.

for getting the desired magnification without their use. If an eyepiece must be used, it should be of very low power, not more than about two times (2×). All the photographs shown were made with achromatic objectives, with but one exception, without the use of eyepieces.

Objectives of long focal length not only give greater depth of focus and less curvature of image, but they also give a larger field

of view and cover a larger plate than those of shorter focal length, so that by their use a larger photograph can be made. It is also desirable that the total area covered by the image at the ground glass screen be much larger than the plate used to record the image, since then only the central portions of the image will be photographed and the best focus, as flat an image as possible under the circumstances and the best definition will be secured. Figures 20, 21, 22, and 23 show that the curvature of the image is less with objectives of greater focal length. The glass scale was not long enough, however, to show the comparative values of the 16 mm and 48 mm objectives in this respect.

VII. PHOTOGRAPHIC PLATES AND THEIR DEVELOPMENT.

The selection of the dry plate to be used in making a photomicrograph is of almost as much importance as any other factor. Various plates were tried during this investigation, and it was found that good results were to be had only by using comparatively slow plates. Even with these plates a contrast developer was used and was found not to give too great contrast if the staining of the fibers was properly done. The slow plate usually has greater resolving power, due to the finer grain of the silver salts in the gelatine emulsion. These advantages will much more than compensate for the additional time of exposure required over that of the faster plate. Process plates, however, are not to be recommended for general work, as they give too much contrast. Whether one should use an ordinary, an orthochromatic, or a panchromatic plate will depend, of course, on the colors of the material to be photographed, the purpose in view in making the photograph, and perhaps on other factors.

VIII. VALUE OF A REPRESENTATIVE FIELD OF FIBERS.

It is of first importance that the microscopist should know the distinguishing properties and characteristics of the fibers which he is about to photograph and that he should take all precaution to get a representative field under the microscope. It would be manifestly wrong, for example, to make a photomicrograph of a field of aspen soda pulp which does not show any of the characteristic pitted vessels chiefly by means of which all hardwoods are distinguished from the softwoods or conifers. It also gives a wrong impression to see a photomicrograph of wood pulp showing an incorrect proportion of fibers to vessels, tracheids, or parenchyma cells. The material to be photographed, whether it be

pulp or other material, should first be studied sufficiently under the microscope to determine its properties and characteristics, and the correct proportion of the various cells or other components, by counting or by some other reliable method. A field for photographing should then be chosen which will show the correct proportion of the various individuals or other characteristics which it is the purpose of the photographer to show.

IX. VALUE OF STAINING.

The utility and value of the use of various stains and dyes in the differentiation and study of plant tissues and elements has long been recognized by botanists. A great number of dyes and stains of recognized worth for botanical work are on the market, and this number is being gradually added to.

A number of these stains are more or less selective in their action on plant tissue, and many of them are emphatically so. Their great value lies in the fact that because of this selective property they dye certain tissues or certain parts of fibers more deeply than others, and thus bring out or accentuate characteristic markings, reactions, or other properties of the fibers. By their use the differentiation and identification of various fibrous materials, otherwise difficult or impossible, is made quite easy and certain.

Their value in the photomicrography of paper-making fibers is greater, if possible, than in the visual study of plant fibers. One of the most serious limitations to the photographing of fibrous materials is that their finer markings and characteristics can not be shown as readily and as distinctly by photographic means as by visual means. Hence any means of showing more distinctly the characteristic markings of fibers is a manifest advantage in making a photograph of these fibers; this means is supplied by the proper use of stains.

Another great value of the use of a proper stain is the contrast afforded between the outlines of the fibers and the background. By this means the fibers may be made to stand out in bold relief, with no suggestion whatever of a background in the finished print if the work is well done.

Figures 24 and 25 show the advantages of staining in bringing out the physical features of fibers, and especially in offering sufficient resistance to the passage of the light rays through the fibers to allow the plate to be exposed long enough to prevent the background showing in the finished print.

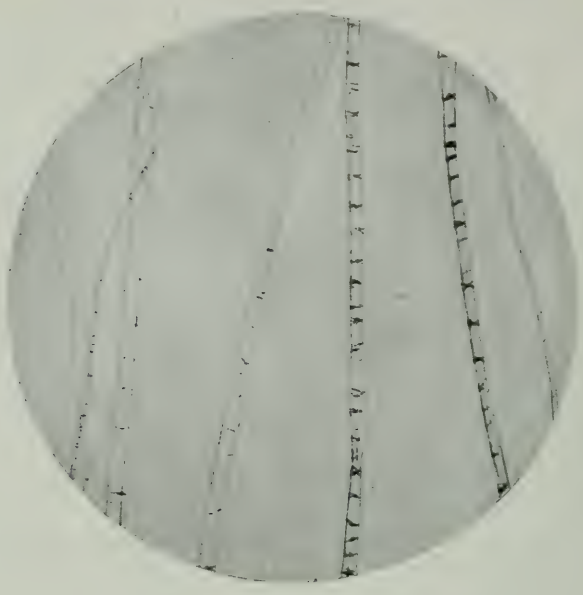


FIG. 24.—*Flax fibers* ×100.

Stain	None
Mounting medium	Venetian turpentine
Objective	16 mm achromatic N. A. 0.25
Diaphragm	4 mm
Exposure	2 minutes

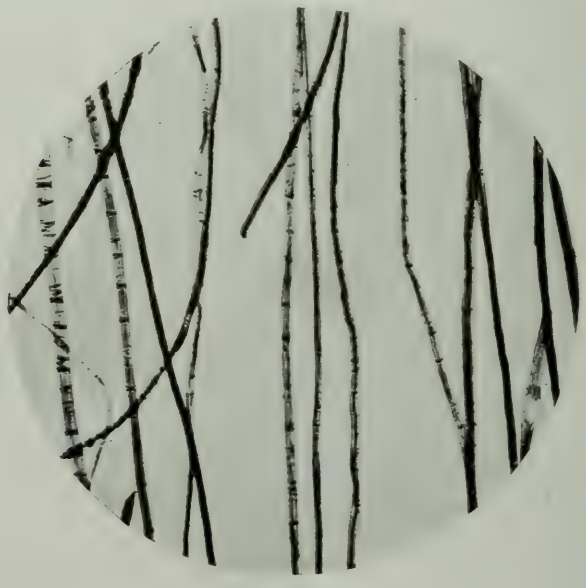


FIG. 25.—*Flax fibers* ×100.

Stain	Methylene blue and saffranin
Mounting medium	Venetian turpentine
Objective	16 mm achromatic N. A. 0.25
Diaphragm	4 mm
Exposure	3 minutes

X. PHOTOGRAPHS AS PERMANENT RECORDS.

The use to which photomicrography may be put in the control of various industrial processes and in recording the presence of adulterations are innumerable. "Wherever the microscope finds application and permanent records of observations are required, photomicrography is the readiest, most convenient, and accurate means available. Prints can be stored with the written notes of analyses and examinations, and have not only the value of records of known facts but of points unknown or unrecognized at the time,

FIG. 26.—*Fibers from all rag heavy ledger* ×100.

Stain	Zinc chloride—Iodine
Mounting medium	Zinc chloride—Iodine
Objective	16 mm achromatic N. A. 0.25
Diaphragm	4 mm
Exposure	1½ minutes

which would inevitably be missed in any written notes, but may become of the highest importance in future researches and afford accumulated evidence which it would be impossible to obtain otherwise." [3]

In the paper industry photomicrography may be advantageously employed in the study and control of the cooking and beating processes, in the examination of pulps and pulp mixtures, and of sizing and loading materials, in recording adulterations frequently found in dyes, in studying bacteria and molds, dirt in pulp and

[3] Hind and Randles, Handbook of Photomicrography, p. 238, London, 1913.

FIG. 27.—*Fibers from all rag medium weight bond ×100.*

Stain	Zinc chloride—Iodine
Mounting medium	Zinc chloride—Iodine
Objective	16 mm achromatic N. A. 0.25
Diaphragm	4 mm
Exposure	1¼ minutes

FIG. 28.—*Fibers from all rag thin bond ×100.*

Stain	Zinc chloride—Iodine
Mounting medium	Zinc chloride—Iodine
Objective	16 mm achromatic N. A. 0.25
Diaphragm	4 mm
Exposure	1½ minutes

paper, and in many other ways. Whatever the eye can see by the aid of the microscope may be recorded photographically if proper methods are used.

Photographs 26, 27, and 28 show the differences in beater treatment for (26) ledger paper, (27) medium-weight bond, and (28) thin bond, and indicate the value of photomicrographs as permanent records.

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WASHINGTON, January 31, 1922.

DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 218

[Part of Vol. 16]

RESULTS OF SOME COMPRESSION TESTS OF STRUCTURAL STEEL ANGLES

BY

A. H. STANG, Associate Physicist

L. R. STRICKENBERG, Assistant Mechanical Engineer

Bureau of Standards

AUGUST 3, 1922

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1922

RESULTS OF SOME COMPRESSION TESTS OF STRUCTURAL STEEL ANGLES.

By A. H. Stang and L. R. Strickenberg.

ABSTRACT.

This article presents the results of compression tests of 170 structural angles, made at the Pittsburgh branch, Bureau of Standards. The object of the tests was to determine the ultimate compressive strength of angles fastened at the ends in such ways as would closely correspond to their connections in the construction of transmission towers. There was also tested a series of angles with square ends. An end fixation factor was found to represent satisfactorily the effect of different types of end connections. Using this fixation factor, the average values for large slenderness ratios were well represented by Euler's formula. The results obtained from shorter columns agreed with the experimental and theoretical results of Kármán. The effect of eccentric loading was most marked at the slenderness ratios indicated by Kármán's theory.

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I. INTRODUCTION.

Compression tests of 170 standard rolled structural steel angles were made at the Pittsburgh laboratory of the Bureau of Standards during the spring of 1917. The specimens tested were all furnished by the tower department of the American Bridge Co., which cooperated in planning the investigation and in carrying out the tests. As the angles were intended for legs and lattice members in electrical transmission tower construction, the greater number were tested with bolted ends, the bolting imitating the riveting used in the construction of the towers. For comparison a number of angles were also tested with flat ends.

II. METHOD OF TESTING.

The specimens were all tested in a 600,000-pound Olsen testing machine. (Fig. 1 shows a general view of the testing machine with an angle under load.) In order to determine the deformation that took place in the angle as the load was applied, a special compressometer was used which was so located as to measure the shortening of the centroidal axis of the specimen. A view of the compressometer attached to a test specimen is shown in Figure 2.

The angles with square ends, having no bolts, were mounted directly between the base and the straining head of the testing machine. In order to test the bolted specimens, special fixtures of structural material were bolted to the base and straining head of the machine and the specimens bolted to these, as shown in Figure 2, a view of the connection used for two bolts in one leg of the angle. A specimen with ends folded is shown in Fig. 3.

The dimensions of the angles are shown in Tables 1 to 7, inclusive, and in Figures 4 to 15 accompanying them. The physical and chemical properties of the material in the angles, obtained incompletely from the mill test reports, are given in Table 8.

TABLE 1.—Results of Compression Tests on Angles with Square Ends, No Bolts.

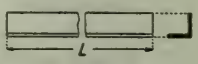

Fig. 4.

Specimen No.	Length L.	Size angle.	Maximum load (lbs./in.²) for slenderness ratio l/r=						
			50	100	150	200	250	300	350
	Ft. in.	Inches.							
A1	5 0	3 by 3 by $\frac{1}{8}$		40,000					
A2	10 0	3 by 3 by $\frac{1}{8}$				26,800			
A3	15 0	3 by 3 by $\frac{1}{8}$						10,750	
A4	2 5½	3 by 3 by ¼	37,000						
A5	4 11	3 by 3 by ¼		36,000					
A6	7 4½	3 by 3 by ¼			32,500				
A7	9 10	3 by 3 by ¼				25,000			
A8	12 3½	3 by 3 by ¼					16,580		
A9	14 9	3 by 3 by ¼						10,750	
A10	17 2½	3 by 3 by ¼							9,000
A11	5 9	3½ by 3½ by ¼		33,000					
A12	11 6	3½ by 3½ by ¼				22,500			
A13	17 3	3½ by 3½ by ¼						12,660	
Average			37,000	36,300	32,500	24,800	16,580	11,390	9,000

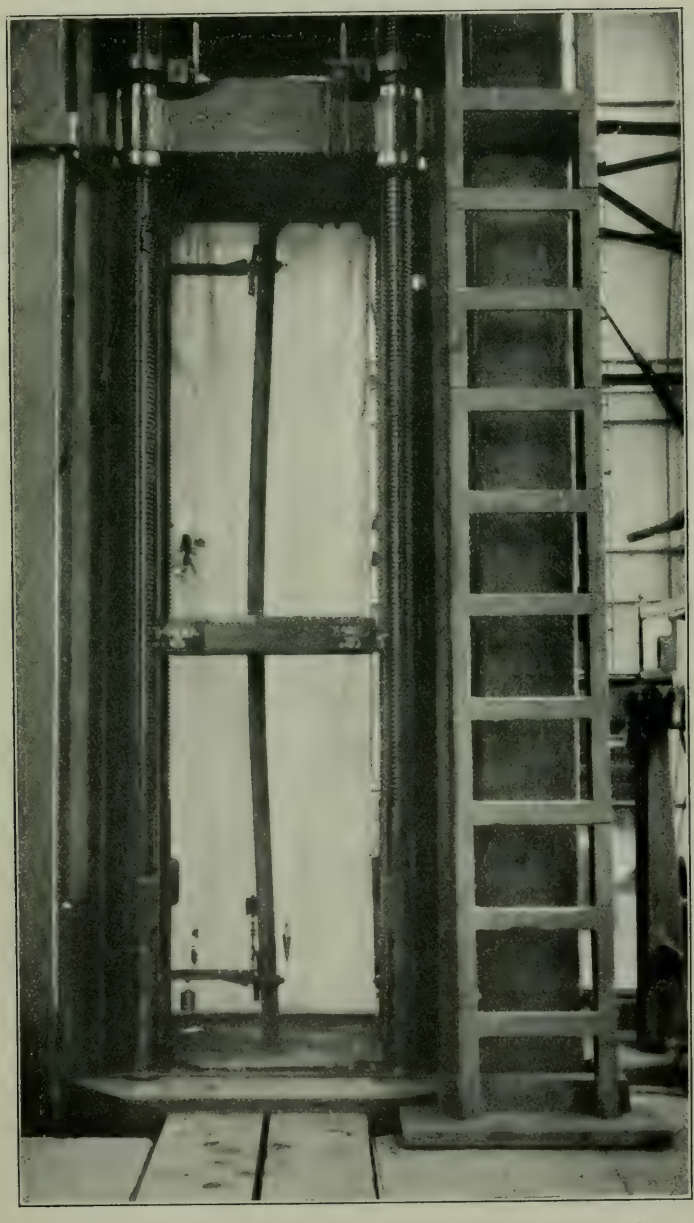

FIG. 1.—*View of the testing machine with an angle under load.*

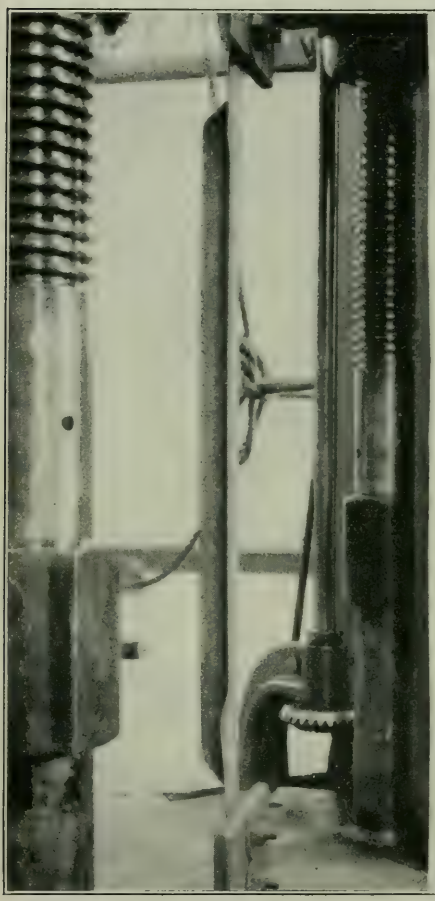

FIG. 3.—*An angle with ends folded, in the testing machine.*

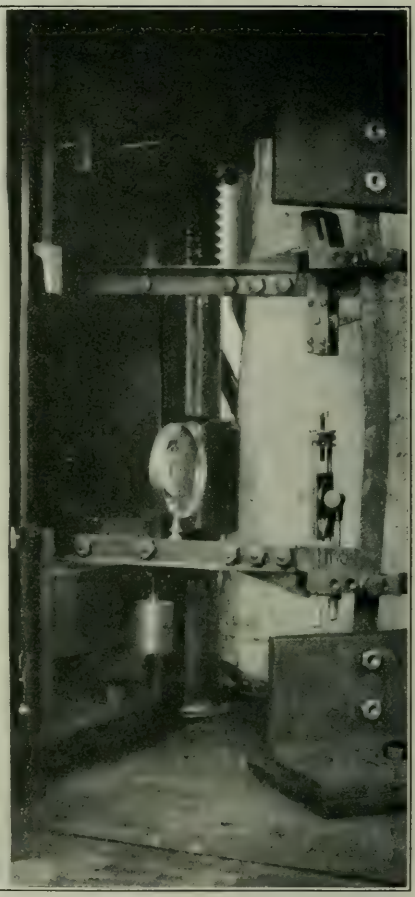

FIG. 2.—*View of compressometer and connections used for fastening a test specimen to the testing machine, two bolts in one leg.*

TABLE 2.—Results of Compression Tests on Angles with One Bolt Connection, Plain Ends.

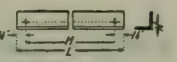

Fig. 5.

Specimen No.	Length L.	Distance. M.	Size angles.	Distance. N.	Diameter of holes.	Maximum load (lbs./in.²) for slenderness ratio 1/r=			
						200	250	300	350
	Ft. in.	Ft. in.	Inches.	Inches.	Inch.				
B1	4 4½	4 2	1¼ by 1¼ by ⅛	5/8	9/16	9,070			
B2	6 5½	6 3	1¼ by 1¼ by ⅛	5/8	9/16			5,380	
B6	4 2½	4 0	1¼ by 1¼ by 3/16	5/8	9/16	10,710			
B7	6 2½	6 0	1¼ by 1¼ by 3/16	5/8	9/16			5,250	
B8	5 2½	5 0	1½ by 1½ by ⅛	11/16	11/16	8,500			
B9	6 5½	6 3	1½ by 1½ by ⅛	11/16	11/16		6,460		
B10	7 8½	7 6	1½ by 1½ by ⅛	11/16	11/16			4,660	
B11	5 0½	4 10	1½ by 1½ by 3/16	11/16	11/16	10,150			
B12	7 5½	7 3	1½ by 1½ by 3/16	11/16	11/16			5,950	
B13	8 6½	8 4	2 by 2 by ⅛	1	11/16		5,210		
B14	10 2½	10 0	2 by 2 by ⅛	1	11/16			4,000	
B17	8 6½	8 4	2 by 2 by 3/16	1	11/16		5,500		
B18	10 2½	10 0	2 by 2 by 3/16	1	11/16			4,450	
B19	10 7½	10 5	2½ by 2½ by ⅛	1¼	11/16		5,500		
B20	12 8½	12 6	2½ by 2½ by ⅛	1¼	11/16			3,350	
B21	14 9½	14 7	2½ by 2½ by ⅛	1¼	11/16				2,610
B22	12 5½	12 3	2½ by 2½ by 3/16	1¼	11/16			4,000	
B23	10 5	10 2½	2½ by 2½ by ¼	1¼	11/16		6,000		
B24	12 5½	12 3	2½ by 2½ by ¼	1¼	11/16			4,760	
B25	14 6	14 3½	2½ by 2½ by ¼	1¼	11/16				3,320
B26	12 8½	12 6	3 by 3 by ⅛	1½	11/16		4,670		
B27	15 2½	15 0	3 by 3 by ⅛	1½	11/16			3,150	
B28	17 8½	17 6	3 by 3 by ⅛	1½	11/16				2,210
B29	15 2½	15 0	3 by 3 by 3/16	1½	11/16			3,890	
B29A	15 2½	15 0	3 by 3 by 3/16	1½	11/16			3,880	
B30	12 6	12 3½	3 by 3 by ¼	1½	11/16		5,500		
B30A	12 6	12 3½	3 by 3 by ¼	1½	11/16		5,400		
BX30	12 6	12 3½	3 by 3 by ¼	1½	11/16		5,420		
B31	14 11½	14 9	3 by 3 by ¼	1½	11/16			3,930	
BX31	14 11½	14 9	3 by 3 by ¼	1½	11/16			4,450	
B32	17 5	17 2½	3 by 3 by ¼	1½	11/16				2,750
BX32	17 5	17 2½	3 by 3 by ¼	1½	11/16				3,270
B33	17 5½	17 3	3½ by 3½ by 3/16	1½	11/16			4,000	
B34	20 4	20 1½	3½ by 3½ by 3/16	1½	11/16				2,920
B35	17 5½	17 3	3½ by 3½ by ¼	1½	11/16			3,540	
B36	20 4	20 1½	3½ by 3½ by ¼	1½	11/16				2,720
B37	11 5½	11 3	3½ by 2½ by ¼	1¼	11/16		5,000		
B38	13 8½	13 6	3½ by 2½ by ¼	1¼	11/16			3,410	
B39	15 11½	15 9	3½ by 2½ by ¼	1¼	11/16				3,500
Average						9,610	5,460	4,240	2,910

TABLE 3.—Results of Compression Tests on Angles with One Bolt Connection in One Leg Only, Ends Folded.

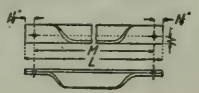

Fig. 6.

Specimen No.	Length L.	Distance M.	Size angle.	Distance N.	Diameter of holes.	Maximum load (lbs./in.²) for slenderness ratio 1/r=		
						100	200	300
	Ft. in.	Ft. in.	Inches.	Inch.	Inch.			
B3	2 3½	2 1	1¼ by 1¼ by ⅛	5/8	9/16	14,900		
B4	4 4½	4 2	1¼ by 1¼ by ⅛	5/8	9/16		9250	
B15	6 10½	6 8	2 by 2 by ⅛	1	11/16		7400	
B16	10 2½	10 0	2 by 2 by ⅛	1	11/16			4500
Average						14,900	8325	4500

TABLE 4.—Results of Compression Tests on Angles with Two Bolt Connections, One Leg Only, Plain Ends.

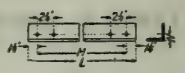

Fig. 7.

Specimen No.	Length L.	Distance. M.	Size angles.	Distance. N.	Diameter of holes.	Maximum load (lbs./in.²) for slenderness ratio l/r=			
						100	150	200	250
	Ft. in.	Ft. in.	Inches.	Inches.	Inch.				
C1	2 5¾	1 10¾	1¼ by 1¼ by 1/8	5/8	9/16	27,200			
C2	2 4¾	1 9¾	1¼ by 1¼ by 3/16	5/8	9/16	24,200			
C3	2 10¾	2 3¾	1½ by 1½ by 1/8	11/16	11/16	23,500			
C3a	2 10¾	2 3¾	1½ by 1½ by 1/8	11/16	11/16	24,000			
C4	4 1¾	3 6¾	1½ by 1½ by 1/8	11/16	11/16		19,470		
C5	2 9¾	2 2¾	1½ by 1½ by 1/16	11/16	11/16	26,900			
C6	4 0¼	3 5¼	1½ by 1½ by 3/16	11/16	11/16		23,400		
C7	5 4¾	4 9¾	2 by 2 by 1/8	1	11/16		15,350		
C8	7 0¾	6 5¾	2 by 2 by 1/8	1	11/16			14,500	
C11	5 4¾	4 9¾	2 by 2 by 3/16	1	11/16		18,500		
C12	7 0¾	6 5¾	2 by 2 by 3/16	1	11/16			14,200	
C13	6 7¾	6 0¾	2½ by 2½ by 1/8	1¼	11/16		13,800		
C14	8 8¾	8 1¾	2½ by 2½ by 1/8	1¼	11/16			10,910	
C15	6 6¼	5 11¼	2½ by 2½ by 3/16	1¼	11/16		17,250		
C16	8 6¾	7 11¾	2½ by 2½ by 3/16	1¼	11/16			13,830	
C17	6 6¼	5 11¾	2½ by 2½ by ¼	1¼	11/16		16,995		
C18	8 6¾	7 11¾	2½ by 2½ by ¼	1¼	11/16			12,780	
C19	7 10¾	7 3¾	3 by 3 by 1/8	1½	11/16		12,400		
C20	10 4¾	9 9¾	3 by 3 by 1/8	1½	11/16			8,950	
C21	10 4¾	9 9¾	3 by 3 by 3/16	1½	11/16			12,520	
C21a	10 4¾	9 9¾	3 by 3 by 3/16	1½	11/16			13,400	
C22	7 9¼	7 2¼	3 by 3 by ¼	1½	11/16		15,210		
C22a	7 9¼	7 2¼	3 by 3 by ¼	1½	11/16		16,400		
C23	10 2¾	9 7¾	3 by 3 by ¼	1½	11/16			11,700	
C23a	10 2¾	9 7¾	3 by 3 by ¼	1½	11/16			12,530	
C24	10 2¾	9 7¾	3 by 3 by 5/16	1½	11/16			11,800	
C24a	10 2¾	9 7¾	3 by 3 by 5/16	1½	11/16			12,570	
C25	12 8¼	12 1¼	3 by 3 by 5/16	1½	11/16				10,000
C25a	12 8¼	12 1¼	3 by 3 by 5/16	1½	11/16				8,350
C26	11 10¾	11 3¾	3½ by 3½ by 3/16	1½	11/16			11,300	
C27	14 9¼	14 2¼	3½ by 3½ by 3/16	1½	11/16				8,350
C28	11 10¾	11 3¾	3½ by 3½ by ¼	1½	11/16			9,870	
C28a	11 10¾	11 3¾	3½ by 3½ by ¼	1½	11/16			10,400	
C29	14 9¼	14 2¼	3½ by 3½ by ¼	1½	11/16				6,300
C29a	14 9¼	14 2¼	3½ by 3½ by ¼	1½	11/16				7,850
C30	14 9¼	14 2¼	3½ by 3½ by 5/16	1½	11/16				8,800
C30a	14 9¼	14 2¼	3½ by 3½ by 5/16	1½	11/16				9,100
C31	9 4¾	8 9¾	3½ by 2½ by ¼	1½	11/16			11,800	
Average						25,200	16,880	12,050	8,400

TABLE 5.—Results of Compression Tests on Angles with Two Bolt Connections, One Leg Only, Ends Folded.

Fig. 8.

Specimen No.	Length L.	Distance M.	Size angle.	Diameter of holes.	Maximum load (lbs./in.²) for slenderness ratio 1/r=	
					50	100
	Ft. in.	Ft. in.	Inches.	Inch.		
C9	2 0¾	1 5¾	2 by 2 by 1/8	11/16	16,530	.....
C10	3 8¾	3 1¾	2 by 2 by 1/8	13/16	.....	18,000

TABLE 6.—Results of Compression Tests on Angles with Two Bolt Connections, One Bolt in Each Leg.

Fig. 9.

Specimens No. D1–D10.

Fig. 10.

Specimens No. E1–E8.

Specimen No.	Length L.	Distance M.	Size angle.	Diameter of holes.	Maximum load (lbs./in.²) for slenderness ratio 1/r=			
					200	250	300	350
	Ft. in.	Ft. in.	Inches.	Inch.				
D1	10 3	10 0	3 by 3 by 5/16	11/16	13,820	.....	.....	.....
D2	12 9	12 6	3 by 3 by 5/16	13/16	.....	10,980	.....	.....
D3	10 1	9 10	3 by 3 by 1/4	11/16	11,620	.....	.....	.....
DX3	10 1	9 10	3 by 3 by 1/4	11/16	12,400	.....	.....	.....
D4	12 6½	12 3½	3 ry 3 by 1/4	11/16	.....	9,760	.....	.....
DX4	12 6½	12 3½	3 by 3 by 1/4	11/16	.....	8,500	.....	.....
D5	10 1	9 10	3 by 3 by 5/16	11/16	13,700	.....	.....	.....
DX5	10 1	9 10	3 by 3 by 5/16	13/16	13,600	.....	.....	.....
D6	11 9	11 6	3½ by 3½ by 1/4	11/16	9,420	.....	.....	.....
D7	14 7½	14 4½	3½ by 3½ by 1/4	11/16	.....	10,300	.....	.....
D8	17 6	17 3	3½ by 3½ by 1/4	11/16	.....	.....	6,520	.....
D9	14 7½	14 4½	3½ by 3½ by 5/16	13/16	.....	9,000	.....	.....
D10	17 6	17 3	3½ by 3½ by 5/16	11/16	.....	.....	6,130	.....
E1	16 8½	16 5½	4 by 4 by 1/4	13/16	.....	5,960	.....	.....
E2	20 0	19 9	4 by 4 by 1/4	11/16	.....	.....	4,530	.....
E3	23 3½	23 0½	4 by 4 by 1/4	11/16	.....	.....	.....	5,000
E4	20 0	19 9	4 by 4 by 5/16	11/16	.....	.....	4,280	.....
E5	16 8½	16 5½	4 by 4 by 3/8	13/16	.....	6,580	.....	.....
E6	20 0	19 9	4 by 4 by 3/8	11/16	.....	.....	4,980	.....
E7	23 3½	23 0½	4 by 4 by 3/8	11/16	.....	.....	.....	4,270
E8	19 9	19 6	4 by 4 by 1/2	13/16	.....	.....	3,930	.....
Average	.....	.....	.....	.....	12,400	8,720	5,060	4,630

TABLE 7.—Results of Compression Tests on Angles with Two or More Bolts in Each Leg.

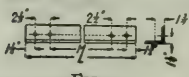

FIG. 11.

Specimens No. D11–D21.

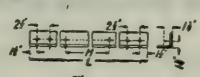

FIG. 12.

Specimens No. D22–D37.

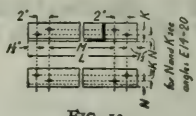

FIG. 13.

Specimens No. E10–E12

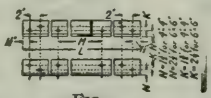

FIG. 14.

Specimens No. E14–E20.

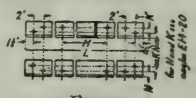

FIG. 15.

Specimens No. E21–E32.

Specimen No.	Length L.	Distance M.	Size angle.	Distance N.	Distance K.
	Ft. in.	Ft. in.	Inches.	Inches.	Inches.
D11	5 5½	4 9½	3 by 3 by 5/16	1¾	
D12	7 11½	7 3½	3 by 3 by 5/16	1¾	
D13	5 4½	4 8½	3 by 3 by ¼	1¾	
D14	7 10	7 2	3 by 3 by ¼	1¾	
D15	7 10	7 2	3 by 3 by 5/16	1¾	
D16	10 1½	9 5½	3 by 3 by ⅜	1¾	
D17	9 1	8 5	3½ by 3½ by ¼	1¾	
D18	9 1	8 5	3½ by 3½ by 5/16	1¾	
D19	11 11½	11 3½	3½ by 3½ by 5/16	1¾	
D20	11 11½	11 3½	3½ by 3½ by ⅜	1¾	
D21	11 9½	11 1½	3½ by 3½ by ½	1¾	
D22	3 2	2 1	3 by 3 by 7/16	1¾	
D23	3 1½	2 0½	3 by 3 by ¼	1¾	
D24	3 4	1 10	3 by 3 by 5/16	1¾	
D25	5 7	4 6	3 by 3 by 5/16	1¾	
D26	3 6	1 7	3 by 3 by ⅜	1¾	
D28	6 4	4 5	3 by 3 by ⅜	1¾	
D28A	6 4	4 5	3 by 3 by ⅜	1¾	
D29	3 9	2 3	3½ by 3½ by ¼	1¾	
D30	6 5	5 4	3½ by 3½ by ¼	1¾	
D31	3 11½	2 0½	3½ by 3½ by 5/16	1¾	
D33	7 8	5 4	3½ by 3½ by 5/16	1¾	
D33A	7 8	5 4	3½ by 3½ by 5/16	1¾	
D34	4 2	1 10	3½ by 3½ by ⅜	1¾	
D35	6 7½	5 1½	3½ by 3½ by ⅜	1¾	
D35A	6 7½	5 1½	3½ by 3½ by ⅜	1¾	
D36	4 4	1 7	3½ by 3½ by ½	1¾	
D36A	4 4	1 7	3½ by 3½ by ½	1¾	
D37	6 9	4 10	3½ by 3½ by ½	1¾	
D37A	6 9	4 10	3½ by 3½ by ½	1¾	
E10	13 7	13 0	4 by 4 by ¼	1½	1⅜
E11	13 7	13 0	4 by 4 by 5/16	1½	1⅜
E12	13 7	13 0	4 by 4 by ⅜	1½	1⅜
E14	7 2	6 3	4 by 4 by ¼	1½	1⅜
E15	4 2½	2 7½	4 by 4 by 5/16	1½	1⅜
E16	10 5½	9 6½	4 by 4 by ⅜	1½	1⅜
E17	7 5	5 10	4 by 4 by ½	1½	1⅜
E18	6 2½	3 11½	6 by 6 by ⅜	2½	2¼
E19	15 5½	14 6½	6 by 6 by ⅜	2½	2¼
E20	20 3	19 4	6 by 6 by ½	2½	2¼
E21	4 0½	2 9½	4 by 4 by ¼	1½	1⅜
E22	7 4	6 1	4 by 4 by 5/16	1½	1⅜
E23	4 4½	2 5½	4 by 4 by ⅜	1½	1⅜
E24	7 4	6 1	4 by 4 by ⅜	1½	1⅜
E25	4 8	2 1	4 by 4 by ½	1½	1⅜
E26	10 8	9 5	6 by 6 by ⅜	2½	2¼
E27	6 4	3 9	6 by 6 by ½	2½	2¼
E28	10 11	9 0	6 by 6 by ½	2½	2¼
E29	15 6	14 3	6 by 6 by ½	2½	2¼
E30	6 11½	3 0½	6 by 6 by ¾	2½	2¼
E30A	6 11½	3 0½	6 by 6 by ¾	2½	2¼
E31	11 2	8 7	6 by 6 by ¾	2½	2¼
E32	12 6	8 7	6 by 6 by ¾	2½	2¼

TABLE 7.—Results of Compression Tests on Angles with Two or More Bolts in Each Leg—Continued.

Specimen No.	Diameter of holes.	Number of holes in each leg.	Maximum load (lbs./in.²) for slenderness ratio l/r=			
			50	100	150	200
	Inch.					
D11	13/16	2		36,800		
D12	13/16	2			26,050	
D13	13/16	2		32,400		
D14	11/16	2			29,900	
D15	11/16	2			29,900	
D16	11/16	2				22,700
D17	13/16	2			25,000	
D18	11/16	2			25,000	
D19	11/16	2				17,700
D20	11/16	2				19,900
D21	11/16	2				15,800
D22	13/16	3	41,000			
D23	11/16	3	35,500			
D24	11/16	4	36,000			
D25	11/16	3		35,300		
D26	11/16	5	35,500			
D28	13/16	5		33,800		
D28A	13/16	5		31,600		
D29	11/16	4	35,000			
D30	11/16	3		33,000		
D31	11/16	5	36,000			
D33	13/16	6		34,000		
D33A	13/16	6		35,700		
D34	11/16	6	38,000			
D35	11/16	4		34,900		
D35A	11/16	4		34,000		
D36	13/16	7	41,800			
D36A	13/16	7	41,200			
D37	11/16	5		34.100		
D37A	11/16	5		33,900		
E10	11/16	2				14,250
E11	13/16	2				16,700
E12	11/16	2				20,150
E14	13/16	3		33,500		
E15	11/16	5	37,000			
E16	11/16	3			25,600	
E17	11/16	5		30,000		
E18	13/16	7	31,600			
E19	13/16	3			22,800	
E20	13/16	3				20,000
E21	11/16	4	37,500			
E22	13/16	4		34,480		
E23	11/16	6	36,200			
E24	11/16	4		33,000		
E25	11/16	8	31,000			
E26	13/16	4		30,200		
E27	13/16	8	28,300			
E28	13/16	6		27,900		
E29	11/16	4			27,750	
E30	11/16	12	31,700			
E30A	11/16	12	32,150			
E31	13/16	8		35,000		
E32	13/16	12		28,820		

TABLE 8.—Results of Tests on Coupon Specimens.

Test numbers.	Size angle.	Chemical analysis (per cent).				Yield point.	Tensile strength.	Elongation in 8 inches.	Reduction of area.
		C.	Mn.	P.	S.				
	Inches.					Lbs./in.²	Lbs./in.²	Per ct.	Per ct.
B1, B2, B3, B4, C1	1¼ by 1¼ by ⅛								
B6, B7, C2	1½ by 1½ by 5/16	0.18	0.43	0.018	0.036				
B8, B9, B10, C3, C4	1½ by 1½ by ⅛	.20	.49	.016	.049				
B11, B12, C5, C6	1½ by 1½ by 5/16	.22	.57	.015	.043				
B13, B14, B15, B16, C7, C8, C9, C10.	2 by 2 by ⅛	.19	.49	.039	.045				
B17, B18, C11, C12	2 by 2 by 5/16	.17	.48	.014	.036				
B19, B20, B21, C13, C14	2½ by 2½ by ⅛			.016	.040	38,160	61,020	27.5	58.6
B22, C15, C16	2½ by 2½ by 5/16			.018	.034	38,480	60,640	28.7	56.0
B23, B24, B25, C17, C18	2½ by 2½ by ¼								
B26, B27, B28, C19, C20	3 by 3 by ⅛					46,680	58,730	28.2	57.4
A1, A2, A3, B29, C21, D1, D2, D11, D12, D22.	3 by 3 by 5/16	.22	.40	.016	.045	37,320	62,300	30.0	54.0
A4, A5, A6, A7, A8, A9, A10, B30, B31, B32, C22, C23, D3, D4, D13, D14, D23.	3 by 3 by ¼	.22	.41	.024	.042	36,710	58,020	28.7	55.7
C24, C25 D5, D15, D24, D25.	3 by 3 by 5/16	.18	.36	.036	.044	36,080	58,980	30.0	53.2
D16, D26, D28	3 by 3 by ⅜	.21	.34	.012	.040	36,840	65,540	27.5	49.6
B33, B34, C26, C27	3½ by 3½ by 5/16	.21	.36	.025	.040	38,000	57,930	28.7	52.8
A11, A12, A13, B35, B36, C28, C29, D6, D7, D8, D17, D29, D30.	3½ by 3½ by ¼								
C30, D9, D10, D18, D19, D31, D33.	3½ by 3½ by 5/16			.011		38,020	60,500	27.5	57.2
D20, D34, D35	3½ by 3½ by ⅜			.016		37,830	60,080	26.2	55.8
D21, D36, D37	3½ by 3½ by ½			.015		38,720	61,980	27.5	55.0
E1, E2, E3, E9, E10, E14, E21.	4 by 4 by ¼	.21	.44	.020	.037	35,850	58,600	26.2	52.2
E4, E11, E15, E22	4 by 4 by 5/16								
E5, E6, E7, E12, E16, E23, E24.	4 by 4 by ⅜								
E8, E17, E25	4 by 4 by ½	.25	.53	.013	.040	35,780	64,750	30.0	50.9
E13, E18, E19, E26	6 by 6 by ⅜	.21	.43	.014	.046	36,200	57,920	30.0	53.9
E20, E27, E28, E29	6 by 6 by ½	.24	.39	.013	.031	36,520	60,090	28.7	52.9
E30, E31, E32	6 by 6 by ¾	.22	.40	.032	.040	36,890	62,950	28.7	52.8
B37, B38, B39, C31	3½ by 2½ by ⅛	.21	.35	.015	.030	36,870	60,780	27.5	52.1

TABLE 9.—Comparison of Lateral Deflection to Strength of Angles with One Bolt Connection.

Specimen No.	Slenderness ratio.	Lateral deflection at 4/9 S.	Rank.		
			By strength.	By deflection.	Difference in—
	1/r	Inch.			
B1	200	0.11	3	2	1
B6	200	.06	1	1	0
B8	200	.17	4	4	0
B11	200	.16	2	3	1
B9	250	.10	1	1	0
B13	250	.20	8	4	4
B17	250	.23	3–5	5	0
B19	250	.19	3–5	2–3	0
B23	250	.19	2	2–3	0
B26	250	.33	10	10	0
B30	250	.25	3–5	6–7	1
B38	250	.31	7	8	1
BX30	250	.25	6	6–7	0
B37	250	.32	9	9	0
B2	300	.13	2	1	1
B7	300	.15	3	2–3	0
B10	300	.16	5	4	1
B12	300	.15	1	2–3	1
B14	300	.17	8–10	5	3
B18	300	.24	6–7	10–11	3
B20	300	.54	16	16	0
B22	300	.25	8–10	12	2
B24	300	.20	4	6–7	2
B27	300	.73	17	17	0
B29	300	.21	12	8	4
B29A	300	.24	13	10–11	2
B31	300	.32	11	13	2
BX31	300	.23	6–7	9	2
B33	300	.20	8–10	6–7	1
B35	300	.40	14	14	0
B38	300	.49	15	15	0
B21	350	.36	7	5	2
B25	350	.27	2	4	2
B28	350	.42	8	6	2
B32	350	.64	5	8	3
BX32	350	.15	3	1	2
B34	350	.21	4	3	1
B36	350	.50	6	7	1
B39	350	.20	1	2	1

TABLE 10.—Comparison of Lateral Deflection to Strength of Angles with Two Bolt Connections in One Leg Only.

Specimen No.	Slenderness ratio.	Lateral deflection at 4/9 S.	Rank.		
			By strength.	By deflection.	Difference in—
	l/r	Inch.			
C4	150	0.12	2	2	0
C6	150	.10	1	1	0
C7	150	.23	7	5	2
C11	150	.17	3	3	0
C13	150	.32	9	9	0
C15	150	.25	4	6–7	2
C17	150	.20	5	4	1
C19	150	.23	10	10	0
C22	150	.27	8	8	0
C22A	150	.25	6	6–7	0
C8	200	.19	1	2–3	1
C12	200	.13	2	1	1
C14	200	.24	13	6–9	4
C16	200	.20	3	4	1
C18	200	.29	5	14	9
C20	200	.26	16	12	4
C21	200	.24	8	6–9	0
C21A	200	.24	4	6–9	2
C23	200	.26	11	11	0
C23A	200	.24	7	6–9	0
C24	200	.27	9–10	13	3
C24A	200	.23	5	5	1
C26	200	.25	12	10	2
C28	200	.35	15	16	1
C28A	200	.30	14	15	1
C31	200	.19	9–10	2–3	6
C25	250	.27	1	1	0
C25A	250	.....	4–5	4	.....
C27	250	.30	4–5	1	3
C29	250	.64	7	7	0
C29A	250	.32	5	5	1
C30	250	.35	3	6	3
C30A	250	.31	2	3	1

TABLE 11.—Comparison of Lateral Deflection to Strength of Angles with Two Bolt Connections, One Bolt in Each Leg.

Specimen No.	Slenderness ratio.	Lateral deflection at 4/9 S.	Rank.		
			By strength.	By deflection.	Difference in—
	l/r	Inches.			
D1	200	0.10	1	4	3
D3	200	.24	5	5	0
DX3	200	.08	4	2	2
D5	200	.05	2	1	1
DX5	200	.09	3	3	0
D6	200	.47	6	6	0
D2	250	.10	1	1–4	0
D4	250	.18	3	5	2
DX4	250	.10	5	1–4	1
D7	250	.10	2	1–4	0
D9	250	.10	4	1–4	0
E1	250	.46	7	7	0
E5	250	.35	6	6	0
D8	300	.27	1	1	0
D10	300	.48	2	4	2
E2	300	.35	4	3	1
E4	300	.81	5	5	0
E6	300	.31	3	2	1
E8	300	1.05	6	6	0
E3	350	.22	1	1	0
E7	350	.35	2	2	0

TABLE 12.—Comparison of Lateral Deflection to Strength of Angles with Two or More Bolts in Each Leg.

Specimen No.	Slenderness ratio.	Lateral deflection at 4/9 S.	Rank.		
			By strength.	By deflection.	Difference in—
	l/r	Inch.			
D11	100	0.03	1	2	1
D13	100	.05	15	5–14	1
D25	100	.05	3	5–14	2
D28	100	.09	11	17	6
D28A	100	.05	16	5–14	2
D30	100	.05	13	5–14	1
D33	100	.05	8	5–14	1
D33A	100	.04	2	3	1
D35	100	.05	5	5–14	1
D35A	100	.05	9	5–14	0
D37	100	.05	7	5–14	0
D37A	100	.05	10	5–14	0
E14	100	.05	12	5–14	0
E17	100	.08	18	16	2
E22	100	.02	6	1	5
E24	100	.08	14	15	1
E26	100	.30	17	19	2
E28	100	.....	20	20	.....
E31	100	.....	4	4	.....
E32	100	.12	19	18	1
D12	150	.10	4	4–5	1
D14	150	.05	1–2	1	0
D15	150	.09	1–2	3	1
D17	150	.10	6–7	4–5	1
D18	150	.06	6–7	2	4
E16	150	.15	5	5	1
E19	150	.22	8	7–8	1
E29	150	.22	3	7–8	4
D16	200	.10	1	4	3
D19	200	.16	4	6	2
D20	200	.05	3	2	1
D21	200	.12	6	5	1
E10	200	.19	7	7	0
E11	200	.07	5	3	2
E12	200	.03	2	1	1

TABLE 13.—End Fixation Factors for Various End Connections of Angles.

End connection.	Fixation factor.	End connection.	Fixation factor.
Angles with square ends, no bolts	1.9	Two bolts, one in each leg	1.3
Two or more bolts in each leg	1.5	One bolt	1.1
Two bolts, in one leg only	1.3	Ends folded	1.1

III. RESULTS AND DISCUSSION OF TESTS.

(*a*) GENERAL DISCUSSION.—The value of the maximum load sustained by each column was measured. These values are given in Tables 1 to 7, inclusive, and have been plotted against the values of the slenderness ratio l/r in Figures 16 and 17. In these figures the average value of the maximum loads for each slenderness ratio is shown by a solid circle. Full lines connect these average values. It will be noted from Figure 17 that for any given slenderness ratio the individual results are quite scattered, and when conclusions are drawn from the average values this fact must be kept in mind.

The manner in which the angles were held in the testing machine exerted a great influence on their strength. In other words, the strength of a column varies with the "degree of end fixation." The amount of this "end fixation" may be expressed by a fixation factor $f = l/L$, where l is the actual length of the member and L the length of the round end member which would fail under the same load; i. e., the "free length" of the member. Thus, the end fixation factor would be 1.0 for a column with round ends and 2.0 for a specimen tested with fixed ends.

The angles with square ends that were placed directly between the head and base of the testing machine would thus have an end

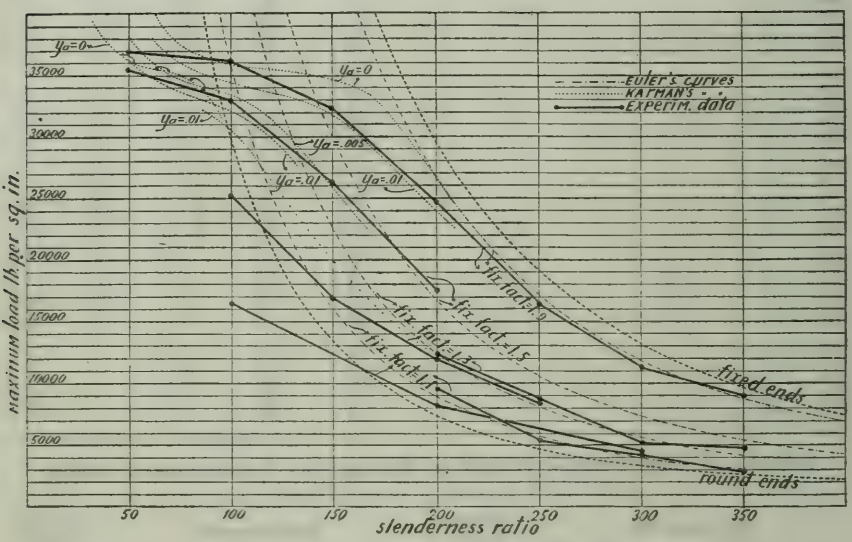

FIG. 16.—*Relation of maximum load to slenderness ratio.*

fixation of approximately the same degree as a column with theoretically fixed ends under axial loading, while specimens that were held with one bolt in one leg would be expected to approximate a round-end specimen under eccentric loading. When more than one bolt is used, the fixation factor would increase and approach 2.0 as the limit for the most rigidly held columns. End fixation factors for various end connections are given in Table 13.

It must be pointed out that in such column tests there is always present some eccentricity, due to imperfect centering in the testing machine and also to the manner in which the load is applied to the specimen, as by bolted connections. It is very difficult to accurately center even a short compression test specimen. The load was eccentric for all the angles bolted to their end con-

nections, and this eccentricity of loading always produces a diminution of the maximum load.

The results of the tests were compared with several types of column formulas. Formulas of the Rankine-Gordon type represent the results fairly well for values of the slenderness ratio up to about 150, but the longer column results are evidently best represented by the Euler formula:

$$\frac{P}{a} = \frac{\pi^2 E}{\left(\frac{l}{fr}\right)^2}$$

where P = total load, pounds.
a = cross-section area, square inches.
E = modulus of elasticity, pounds per square inch.
l = length of column, inches.
r = radius of gyration, inches.
and f = fixation factor.

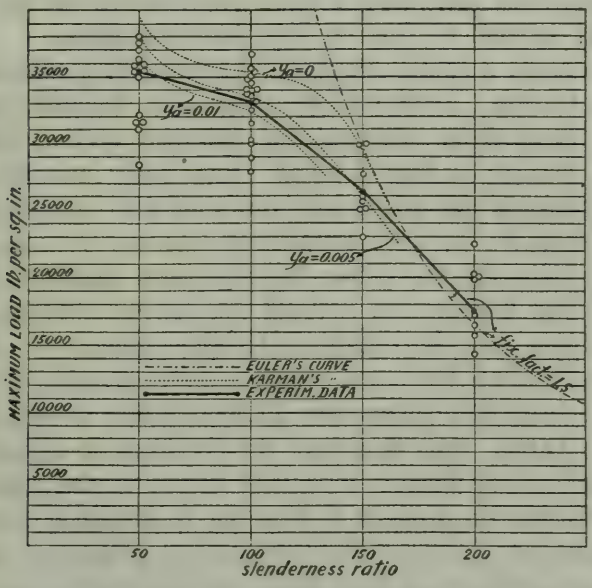

FIG. 17.—*Relation of maximum load to slenderness ratio for fixation factor* $f = 1.5$.

The Euler formula does not give the strength of short columns, however, since for such lengths the elastic limit of the material is passed before the column fails. The theory of the deviation of short columns from Euler's law has been worked out by Considére (K. Considére, Résistance des Pièces Comprimées, Comptes Rendus, Congrès International des Procédés de Construction, pp. 371–397, 1891), Jasinsky (Jasinsky, Zu den Knickfragen, Schweiz. Bauzeitung, vol. 25, p. 172, 1895), and Kármán (Theo. von Kár-

mán, Untersuchung über Knickfestigkeit, Forschungsarbeiten a. d. Gebiete d. Ingenieurwesens, No. 81, 1910), and later independently by Southwell (R. V. Southwell, The Strength of Struts, Engineering, vol. 94, pp. 248–250, 1912; Aircraft Engineering, vol. 1, p. 20 et seq., January, 1920). The theoretical curve given by Kármán for a steel whose physical properties had been determined were recalculated for a yield point of 37,000 lbs./in.^{2} and a modulus of elasticity of 30,000,000 lbs./in.^{2} They were found to agree with the results of these tests when the end fixation factor was taken into account and the effect of eccentricity noted. This curve, which goes over into the Euler hyperbola for large values of the slenderness ratio, has been plotted for comparison with the average results of this test.

In Figures 16 and 17 the dashed curves represent the Euler formula for round and for fixed ends, as shown. The dash-and-dot curves shown represent the intermediate degree of end fixation for the Euler and their dotted continuation for the Kármán values that seemed to best fit the particular case.

Kármán made a special study of the effect of eccentric loading in column testing. It should be noted that the unit stresses he found are those from tests on 0.50 per cent carbon steel. The important feature is that a small eccentricity has the greatest effect in reducing the maximum unit load for values of slenderness ratio from 80 to 85 for round end columns ($f = 1.0$), and this is probably true for the milder steel in these angles. For other degrees of end fixation the critical slenderness ratio is obtained by multiplying, say, the value 85 by the value of f. It will be seen in the detailed discussion that the average value of the maximum unit load falls below the Kármán-Euler curves for these slenderness ratios, thus denoting the presence of eccentricity.

Since the lateral deflection at mid height of the columns was measured during the tests, it is possible to obtain a rough comparative measure at least of the eccentricity of the test specimens. For a column with fixed ends there can be no effective eccentric loading. The load, no matter how far its point of application is from the centroidal axis of the column, can only produce such stresses in a fixed end specimen as would be produced by a load concentrically applied. The reason for this is that the definition of a "fixed end" column presupposes that the tangent to the elastic curve at one end is parallel to and remains parallel to the tangent at the other end. In a testing machine, if the columns were really to have fixed ends, the bearing plates would remain

parallel to each other throughout the test, and all effects of the eccentric loading would be taken up by the supporting screws of the testing machine. As a matter of fact, however, it is impossible to maintain this theoretical condition of fixed ends under an eccentric load either in a testing machine or in a built-up structure, and the column strength will be reduced if the load is applied eccentrically.

From the elastic theory one may express the relation between the lateral deflection at mid height, y_m, and the initial eccentricity, y_a, for round end columns, as follows:

$$y_m = y_a\left(\frac{1}{\cos\frac{l}{2r}\sqrt{\frac{P^1}{aE}}} - 1\right)$$

where P^1 is the load which produced the deflection y_m. Now, there is some value of $P^1 = kP$ (P being the value of the maximum load from Euler's formula) for which the lateral deflection y_m is equal to the initial eccentricity y_a. Solving for k under this condition, $k = 4/9$. That is, in a perfectly elastic round end column of any slenderness ratio the deflection at mid height when the load is 4/9 of the theoretical maximum is equal to the initial eccentricity of load. For other degrees of end fixation this ratio would be different, but for the sake of comparison Tables 9 to 12 show the lateral deflection at mid height which occurred at the unit loads $S^1 = 4/9\,S$. It is assumed that the value of the theoretical unit load S is given by the dash-and-dot curves of Figures 16 and 17. Any other definite ratio might have been chosen for the comparison, provided the ratio were small enough, but the comparative results would have been practically the same. No claim is made that these values represent the actual initial eccentricity. It is, however, evident that in practically all cases the specimen of given slenderness ratio and degree of end fixation which sustained the highest unit load also suffered the least lateral deflection at the unit load S^1, while the specimen which suffered the greatest lateral deflection sustained the least unit load. Tables 9 to 12 also give the "rank" of the specimens according to strength and to lateral deflection. With very few exceptions the rank of a specimen is practically the same by either method of ranking.

One might conclude, then, from these results that the theoretical load-slenderness ratio curve for zero eccentricity should be drawn somewhat above the largest load values, and thus obtain a different value of fixation factor from the value obtained by considering the mean of the test results. It must, however, be pointed out

that the specimens closely represented the conditions in actual construction, and no better centering of a member would be obtained on the average than was obtained in these tests. The mean results are therefore of more importance in design than any such theoretically determined values would be.

(*b*) DETAILED DISCUSSION OF RESULTS.—Figure 16 shows the results of tests of angles with square ends. The average result line is close to the fixed end curve (dotted), but agrees still better with the dash-and-dot curve plotted for $f = 1.9$. At $l/r = 200$ the average result is below the curve, and it is in this region that the most marked effects of eccentric loading are to be expected.

When the angles were tested with one bolt connection—in one leg only, approximately round end columns,—the results are close to the curve of end fixation, for $f = 1.1$. No appreciable effect of eccentricity in loading in reducing the maximum load appears here in the average results because the slenderness ratio is so much greater than 85.

The results of tests of angles with folded ends, do not fall so close to the curve for $f = 1.1$ as did those just considered. So few specimens of this class were tested that it is impossible to draw any definite conclusion whether this type of column curve is suitable for angles with ends folded. It must also be noted that angles with ends folded, as shown in Figures 3, 6, and 8, have a variable radius of gyration from section to section. The ordinary column formulas are not derived for such conditions.

Figure 16 shows also the results of the tests of specimens held at each end with two bolts, in one leg only. This manner of fastening is more rigid than when a single bolt is used and the results for the columns with slenderness ratio as large as 200 lie close to the Euler curve for $f = 1.3$. For shorter columns the average results lie below this curve, and this may be due to the eccentric loading which would have the greatest effect at $l/r = 110$.

When two bolts are used, one in each leg, the degree of end fixation appears to be the same as for the previously considered class, and the results fall very close to the Euler curve for $f = 1.3$. The lengths tested in these two classes overlap for the slenderness ratios 200 and 250, and the average results for each of these slenderness ratios are nearly equal. The strength of the angles held with two bolts, in one leg only, is apparently the same as for specimens held with two bolts, one in each leg.

When two or more bolts were used in each leg for fastening the angle to the testing machine, the end fixation factor is still

larger, and the curve for $f = 1.5$ of the Kármán-Euler type represents the average results very well, as shown in Figures 16 and 17. Here, again, the eccentricity lowers the average result value at the critical slenderness ratio value, $85 \times 1.5 = 127.5$, and is visible at $l/r = 150$. When angles are held as rigidly as these were, it might have been expected that the end fixation factor would have been closer to the fixed end condition, $f = 2.0$. It may be that the factor is no higher than 1.5 because of the deformation which doubtless occurred in the structural members to which the test pieces were bolted.

IV. CONCLUSIONS.

1. The values of the maximum unit load in these tests vary over a considerable range for any given slenderness ratio and manner of fastening the angles in the testing machine.

2. In most cases the specimen which sustained the greatest unit load for a given slenderness ratio and method of fastening suffered the least lateral deflection and the angle which bent most sustained the lowest unit load at failure, the deflection being measured at 4/9 of the theoretical maximum load.

3. For large slenderness ratios the average values are well represented by Euler's formula for long columns, calculated for different values of the end fixation factor.

4. The Kármán curves, recalculated for a yield point of 37,000 lbs./in.^{2} and modulus of elasticity of 30,000,000 lbs./in.^{2} represent the average results for small slenderness ratios for several methods of end fixation, except in the neighborhood of $l/r = 80$ to 85, where the effect of eccentricity was greatest. The values of the end fixation factor are given in Table 13.

5. For angles with ends folded the column formulas considered do not represent the results found in this series of tests.

6. It is believed that these values of end fixation factor are of importance in the design of structures where the end conditions approximate those used in these tests, no matter what formula the designer prefers to use.

7. Eccentricity of loading produces a diminution of column strength. In these tests the greatest effect of eccentricity was observed in the neighborhood of a "free length" corresponding to $l/r = 85$, which agrees with the results of Kármán's investigations.

WASHINGTON, April 12, 1922.

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EFFECT OF TEMPERATURE, DEFORMATION, AND RATE OF LOADING ON THE TENSILE PROPERTIES OF LOW-CARBON STEEL BELOW THE THERMAL CRITICAL RANGE

BY

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Bureau of Standards

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EFFECT OF TEMPERATURE, DEFORMATION, AND RATE OF LOADING ON THE TENSILE PROPERTIES OF LOW-CARBON STEEL BELOW THE THERMAL CRITICAL RANGE

By H. J. French

ABSTRACT

An apparatus for determining tensile properties of metals at high temperatures (including limit of proportionality) and the results of tests of several grades of boiler plate from 20 to 465° C. are described. The effects of cold and blue work on the properties of these steels throughout the range given are discussed, and in addition, some results are given showing the effect of tensional elastic overstrain on the proportional limit at different temperatures and its subsequent behavior with time. Effects of variations in rates of loading (both rapid and slow) and the modified apparatus used for this work are also described.

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I. INTRODUCTION

During 1919 the Bureau of Standards was requested by a committee of the engineering division,[1] National Research Council, to determine the effects of cold work on the proportional limit of boiler plate at elevated temperatures, as a result of a similar request received by this committee. Following the early work of development of a suitable apparatus for such tests about July, 1919, and the determination of the tensile properties of the hot-rolled steel for a basis of comparison, there arose the questions of deformation in the "blue-heat range" and the effects of variations in rate of stress application on the properties of steel at high temperatures, so that the original program was greatly extended.

The complete research necessitated investigation along five different lines, which may be summarized as follows:

1. Development of apparatus for determination of the limit of proportionality at various temperatures, and investigation of the tensile properties of several grades of boiler plate up to about 465° C (870° F).

2. Effect of permanent deformation (by rolling cold and at blue heat) on the properties of steel at different temperatures.

3. Study of the behavior of steel subjected to tensional elastic overstrain at several temperatures.

4. Effect of rate of stress application on the tensile properties of hot-rolled boiler plate at various temperatures.

5. Microscopic examination.

As progress was made in this work new questions arose, but because of the almost unlimited field for investigation it was not possible to follow more than a few of such leads or to satisfy these inquiries. The tests are not considered complete in any of the several phases dealt with, but are presented as detailed data relative to several questions concerning which there have

[1] Committee on Physical Changes in Iron and Steel below the Thermal Critical Range. Dr. Zay Jeffries, chairman.

been conflicting opinions and likewise show effects, which, as far as the author is aware, have not before been so completely determined quantitatively. In some cases the practical applications of results of tests are indicated, while at the conclusion of the report is given a selected bibliography on the mechanical properties of steels at high temperatures, which will be referred to throughout the text as required.

II. TENSILE PROPERTIES OF STEELS AT HIGH TEMPERATURES

1. PREVIOUS INVESTIGATIONS

It has long been known that increase in temperature above the ordinary atmospheric range is accompanied by changes in steels, particularly in strength and ductility. A large number of interesting and important papers dealing with various phases of this subject have appeared from time to time, but as recently pointed out by Jeffries (34) [2] our knowledge is still unsatisfactory, and a better understanding of these changes will undoubtedly be of benefit to industry. White (35) is of the opinion that our knowledge of the tensile properties of steels at high temperatures is wholly inadequate and has not kept pace with advancement of knowledge in other branches of engineering, while Howe (38) long ago called attention to the apparent anomalies found in studying the effects of work at temperatures under the thermal transformations on the properties of wrought iron and steel used in boiler construction. Certainly, from the standpoint of engineering design, it is important to know the variations in limit of proportionality with changes in temperature, but unfortunately this is the more difficult to determine of those factors considered in tensile tests, and the data available are conflicting.

In Figures 1A and 1B is given a summary of results obtained in some of the more important published investigations of the tensile properties of steels and wrought iron at high temperatures.[3] Increase in strength with first rise in temperature above that of the room is reported by Rudeloff (9), (13), Huntington (24), Epps and Jones (32), and Bregowsky and Spring (25), while Martens (7), Perrine and Spencer (30), and J. E. Howard (8) find a slight decrease between about 50 and 150° C (125 and

[1] These figures relate to the numbered references in the "Selected bibliography" at the conclusion of this paper.

[2] Refer to the bibliography at the conclusion of this report for more complete data.

300° F), which is followed by increase to a maximum between 205 and 345° C (400 and 600° F). In a very complete series of tests of steels of varying carbon contents Howard further found that the minimum tensile strength occurring with first rise in temperature was generally more quickly reached the lower the carbon content,

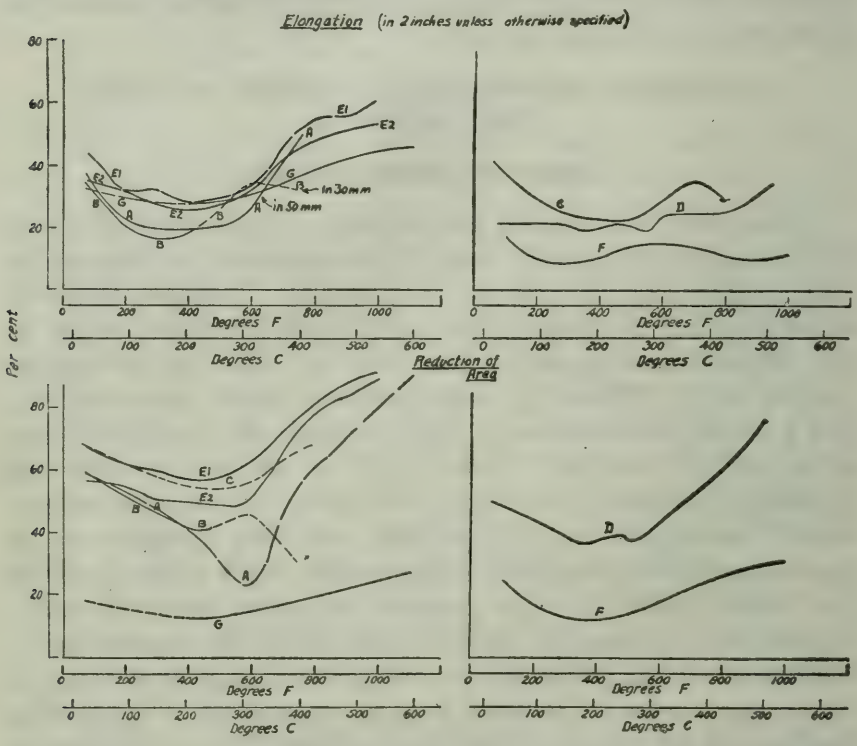


FIG. 1A.—*Tensile properties of wrought iron and steels at various temperatures as determined by different investigators*

A Martens (1890), "Hartestufe"
B Rudeloff (1893), Martin Stahl
C Huntington, mild steel
C_1 Huntington, wrought iron
D Bregowsky & Spring, cold-rolled Bessemer shafting
E_1 Perrine & Spencer, 0.23 per cent C, Bessemer steel
E_2 Perrine & Spencer, 0.39 per cent C, Bessemer steel
F Epps and Jones, wrought iron
G Shelby Laboratory, 0.36 per cent C steel

and that the higher carbon steels attained their maximum strength at lower temperatures than medium or low-carbon alloys (Fig. 2).

Various investigators have from time to time reported decrease in elastic properties with increase in temperature, but one of the earlier investigators, Martens (7), has distinguished between the gradual decrease in yield point and the behavior of the propor-

tional limit which, after a slight decrease at about 100° C (210° F) in "soft steel," increased to a maximum at 200° C (390° F) before final decrease occurred. Epps and Jones obtained similar inflections in a proportional limit temperature curve for wrought

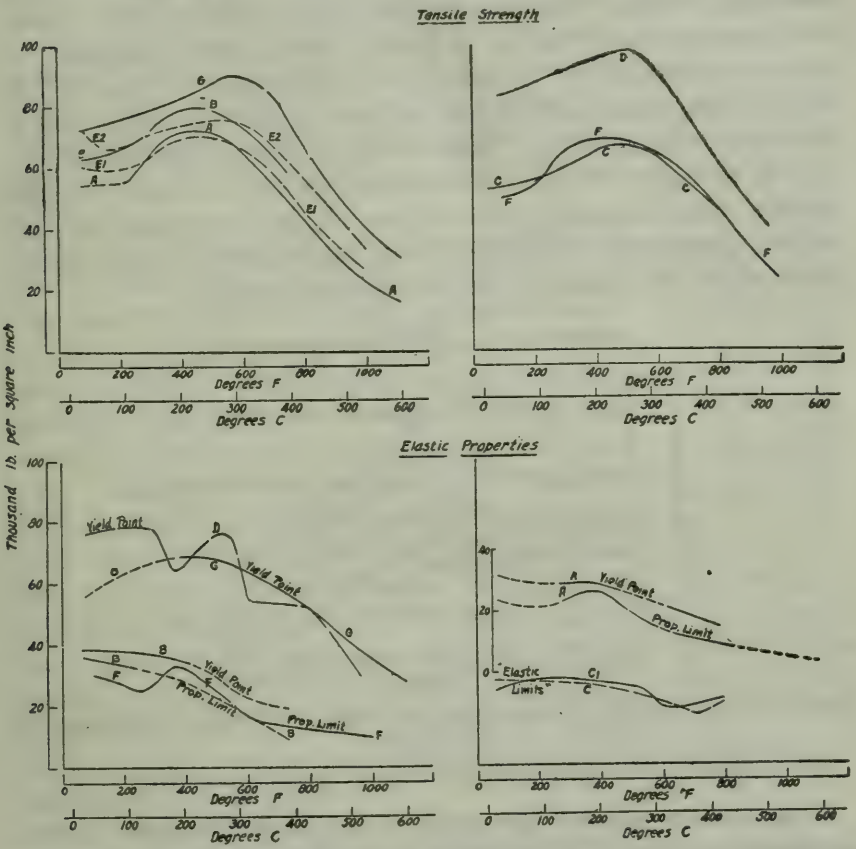


FIG. 1B.—*Tensile properties of wrought iron and steels at various temperatures as determined by different investigators*

A Martens (1890), "Hartestufe"
B Rudeloff (1893), Martin Stahl
C Huntington, mild steel
C_1 Huntington, wrought iron
D Bregowsky & Spring, cold-rolled Bessemer shafting
E_1 Perrine & Spencer, 0.23 per cent C, Bessemer steel
E_2 Perrine & Spencer, 0.39 per cent C, Bessemer steel
F Epps and Jones, wrought iron
G Shelby Laboratory, 0.36 per cent C Steel

iron with first decrease at a slightly higher temperature and the maximum at about 180° C (360° F), while both the Shelby laboratory [4] and Bregowsky and Spring (25) report direct increase in yield point to a maximum at about 200° C (390° F).

[4] Private communication from Luken's Steel Co., 1920.

In his tests Howard (8) found that the interval between the elastic limit and the maximum stress showed particularly interesting features. Several of the different steels tested showed a yield point at the elastic limit, this period being marked by rapid stretching which, once begun, continued under reduced loads. Such yielding rarely occurs in testing steel at room temperature, but was observed by Howard up to about 260° C (500° F) in tests of mild steels and at temperatures somewhat below this in the higher carbon alloys. Bars tested between about 95 and 205° C (200 and 400° F) showed alternate periods of relaxation and rigidity under increasing stress resembling a succession of yield points, apparently indicating some remarkable changes taking place within the metal in this temperature range.

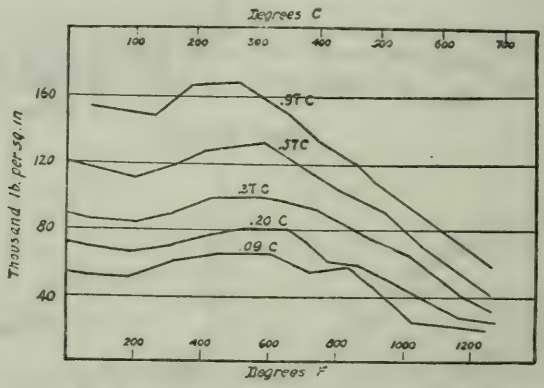


FIG. 2.—*Tensile strength of carbon steels at various temperatures as determined by J. E. Howard*

See Physical properties of iron and steel at higher temperature. Iron Age, 45, p. 585; 1890

There is more general agreement in various publications regarding changes in ductility as measured by elongation and reduction of area. Elongation decreases slowly just above room temperature and thereafter more rapidly to a minimum variously reported as occurring between 125 and about 200° C (255 and 390° F). It then increases rapidly. Reduction of area likewise decreases but little just above the temperature of the room, but then drops rapidly to a minimum reported to occur between 200 and 300° C (390 and 570° F), which is higher than the temperature of occurrence of minimum elongation and is followed by rapid increase in values. Howard (8) also found a tendency for bars broken at temperatures between 205 and 315° C (400 and 600° F) to fracture in an oblique shearing direction.

2. MATERIALS AND METHODS USED

(*a*) STEELS TESTED.—The steels tested in this investigation were received as half-inch boiler plates of fire box and marine grades. The specified tensile strength and composition for each are shown in Table 1, but the third class listed showed slightly higher tensile values than the limits prescribed and was supplemented by class 4. The former was used, however, and the tensile properties at high temperatures of the hot-rolled steel were determined because the number of plates of the first two series was insufficient for completion of the desired tests.

The steels were made in the basic open hearth and the baths kept in a boiling condition up to the moment of casting. Such metal is often referred to as "open steel" to distinguish it from that which has been "killed" in the ordinary manner. It is porous in its cast condition and shows some segregation, but is nearly free from pipe. Variations in composition have, however, been kept to a minimum by cutting the patterns from which the test specimens were machined from steel originally in the central and least segregated portion of the ingot, but unfortunately no detailed record of this procedure is available except in the case of series 4, where the patterns were distributed as given in Figure 3. Check analyses show excellent uniformity and agree closely with the compositions shown in Table 1.

FIG. 3.—*Distribution of patterns cut from railway firebox plate (Series 4 Steel)*

TABLE 1.—Steels Tested

Series	Grade	Specified tensile strength	Composition			
			C	Mn	P	S
		Lbs./in.²	Per cent	Per cent	Per cent	Per cent
1	A. S. T. M. fire box[1]	52 000–62 000	0.19	0.43	0.020	0.031
2	Marine	60 000–70 000	.25	.38	.019	.031
3	Railway fire box	45 000–55 000	.17	.36	.024	.031
4	Railway fire box	45 000–55 000	.18	.43	.017	.035

[1] American Society for Testing Materials, fire-box steel. Specification A 30–18.

A detailed description of ingots and plates produced in the manner referred to above is contained in a report by Charles Huston,[5] which includes many excellent photographs and charts showing the porosity of the cast metal and the chemical and physical characteristics of the rolled plates.

TABLE 2.—Ingot Size and Rolling Record of Steels Tested

Series	Original weight	Ingot size	Reduction in rolling	Pattern size
	Pounds	Inches		Inches
1	5900	36 by 15	30 to 1	36 by 18
2	5650	32 by 12	24 to 1	36 by 12
3	3150	26 by 12	24 to 1	36 by 18
4	3150	26 by 12	24 to 1	40 by 15

In Table 2 is given a record of original ingot size and reduction in rolling the various plates tested in this investigation. Flat test bars, with long dimension in the direction of rolling, were cut from patterns taken from these plates and machined to the form shown in Figure 4.

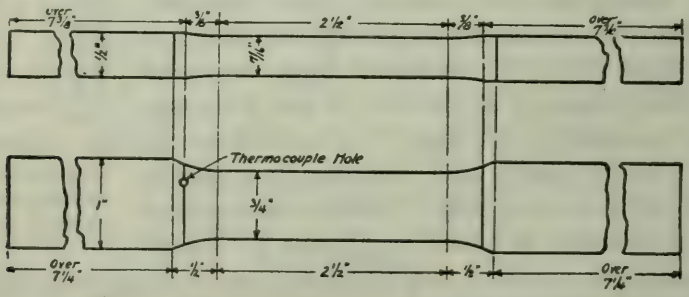


FIG. 4.—*Form and dimensions of test specimen used*

(*b*) APPARATUS FOR DETERMINATION OF PROPORTIONAL LIMIT.—At the outset emphasis is laid on the fact that, for the work required throughout the various sections of this investigation, suitable and readily manipulated apparatus and not the most accurate mechanism available was sought. The material under test is lacking in entire uniformity (which condition is usual in engineering material), so it appeared undesirable to construct elaborate equipment requiring a great deal more time in development and actual test.

[5] C. L. Huston, Experiments on the segregation of steel ingots in its relation to plate specifications, Proc. Am. Soc. Test. Mat. 6 (1906), p. 182.

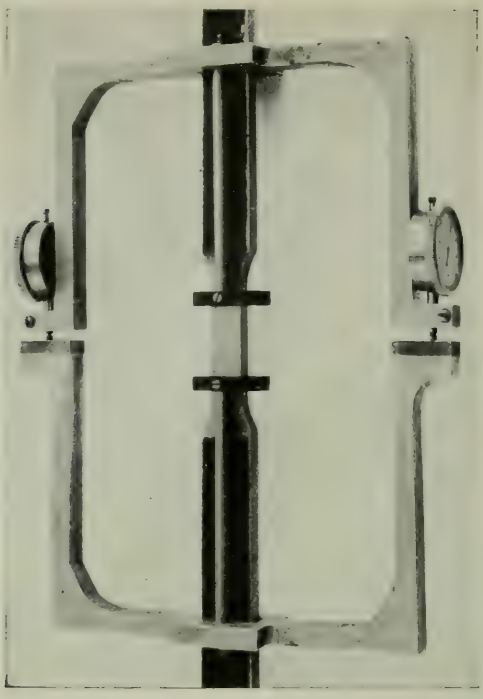


FIG. 5.—*Apparatus used for determining proportional limit*

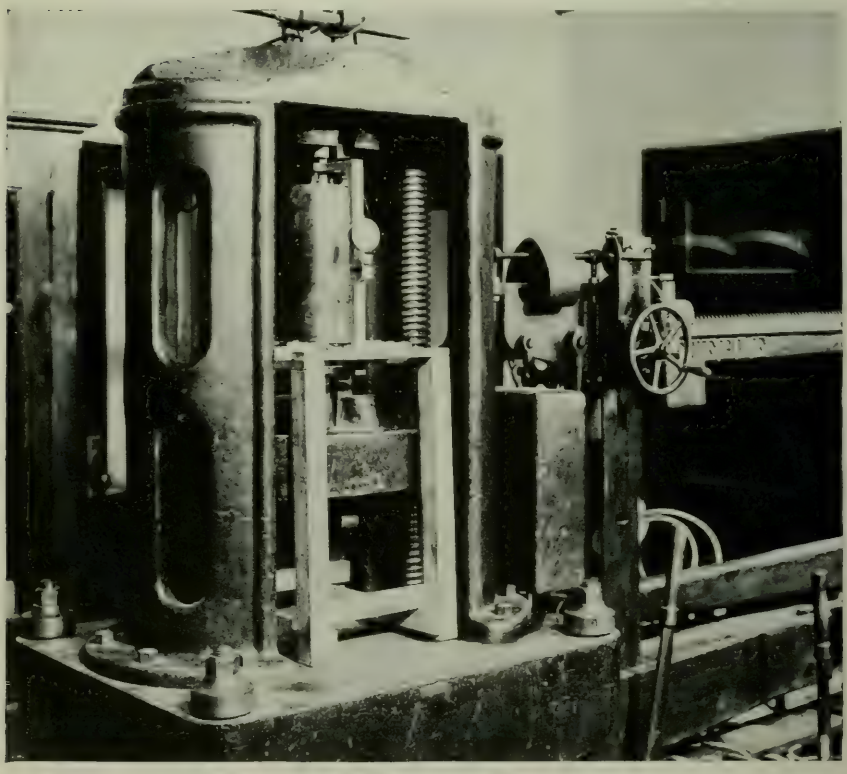


FIG. 8.—*Apparatus for determining tensile properties of metals at high temperatures*

The apparatus used in determination of the limit of proportionality at various temperatures is shown in Figure 5 and consisted primarily of two aluminum-alloy frames each rigidly fastened to a quenched and tempered steel yoke (shown in Fig. 6) by two annealed low-carbon steel rods. The specimen passed freely through the holes in the base of each of the frames. Yokes were each clamped to the specimen by three quenched and tempered high-speed steel screws, while the spreading of the former was overcome by the long screw. The flanges on the upper frame were so arranged that dial micrometers for indicating deformation might readily be securely fastened to them, while those of the lower frame were capped with polished steel plates to give a smooth bearing surface to the plungers of the dials.

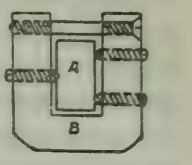


FIG. 6.—*Yoke*

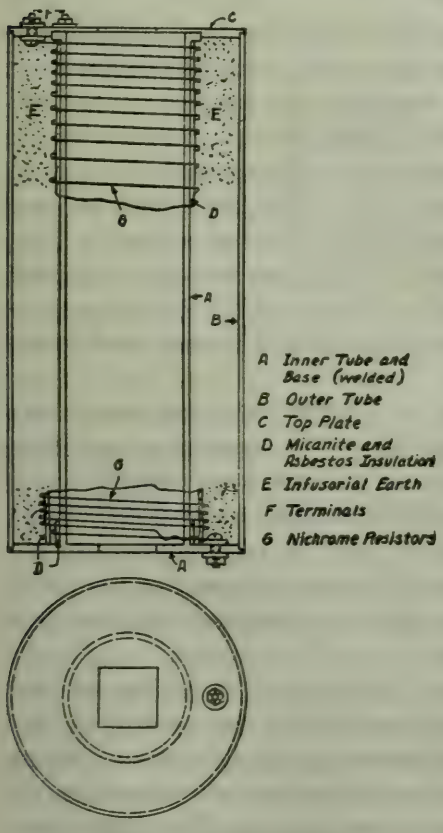


FIG. 7.—*Heating furnace*

The smallest division on the instruments used was equal to 0.001 inch, but estimated readings to the nearest 0.0001 inch were readily obtained. When stress is applied to the specimen, half the algebraic sum of the deformation recorded by the two dials represents the deformation of the specimen, which is centrally located with respect to the entire apparatus. For example, upon application of load the apparatus may twist to some extent, the dial on the left showing a negative deformation (decrease in length) of 0.004 inch, while that on the right registers a positive deformation (increase in length) of 0.009 inch. Half the algebraic sum ($\frac{1}{2}$ (+0.009 inch − 0.004 inch) = 0.0025 inch) represents the deformation (increase in length) of the specimen under the load applied.

(*c*) HEATING FURNACE.—The test specimens were heated by means of an electric tube furnace of the form shown in Figure 7. Two spiral resistors in series were used. The one covered the entire length of the inner tube (11 inches) and the other was concentrated at the ends, the two requiring about 80 feet (24 m) of 22-gage nichrome wire. Yokes and the greater part of the 18-inch (46 cm) test bar and rods were contained in the heating chamber, which was 11 inches long. A comparatively small temperature gradient was obtained under suitable operating conditions, as the effective heating length during test was about one-third of this at the center of the tube length, or approximately 3 inches. The furnace was operated on either 110 or 220 volts, direct current, close regulation being obtained by variable resistance in series in the circuit.

(*d*) TEST PROCEDURE.—The method of setting up the apparatus, together with procedure followed in actually carrying out the tests, was substantially as follows: A specimen was marked on one surface with a double-pointed center punch leaving marks 2 inches apart. Next, the yokes were attached to the specimen by setting the single screw into these impressions. Then, by lightly tapping the opposite side of the yoke containing the two screws, a light impression of their exact location on the test bar was obtained. These points were then enlarged by the use of the double-pointed center punch, and the yokes carrying rods and frames were firmly attached to the test piece.

Bolts holding the upper frame to the two rods were next taken off and the upper frame removed. The specimen was then passed up through the furnace until the rods appeared above the top, when the upper frame was again fastened to the rods. After the furnace was placed on a stand and the specimen was in the jaws of the testing machine the dials were attached to the frame and adjusted to zero. The completely assembled apparatus is shown in Figure 8.

When thermal equilibrium at the desired temperature was reached, an initial load of about 1500 lbs./in.^{2} was applied and the dials read or, as a matter of convenience, again set at zero. Readings were then taken at increments of 500 or 1000 pounds actual load until the proportional limit was passed. The dials were then removed and the specimen was broken in the usual manner with a low rate of extension which approximated the intermittent increases of stress applied during determination of the limit of

proportionality. Tests at each temperature were made in duplicate or triplicate, and the proportional limit was obtained from a stress-strain diagram. Typical curves obtained from tests at various temperatures throughout the range covered are shown in Figure 9. Temperature was measured by a 22-gage standardized chromel-alumel couple connected to a Leeds & Northrup portable potentiometer. The end of the couple was inserted directly into a small hole drilled in the specimen at the fillet, its exact location being shown in Figure 4.

(*e*) THERMAL EQUILIBRIUM.—In order to obtain reliable and satisfactory results with the method described in the preceding paragraphs, thermal equilibrium must be reached prior to the start of the loading and maintained during the actual 8 to 15 minutes during which the test is being carried out. The adjustable resistance in series in the electrical circuit makes current adjustment possible, so that the loss of heat from the heating unit, ends of test specimen, and auxiliary apparatus by radiation, convection, and conduction balances the energy added to this entire system. The effect of temperature variations may be large unless care is taken to allow sufficient time for the specimen to become uniformly heated throughout after the potentiometer has once indicated the desired temperature. The dial readings will assist in determining when equilibrium has been reached and is being maintained.

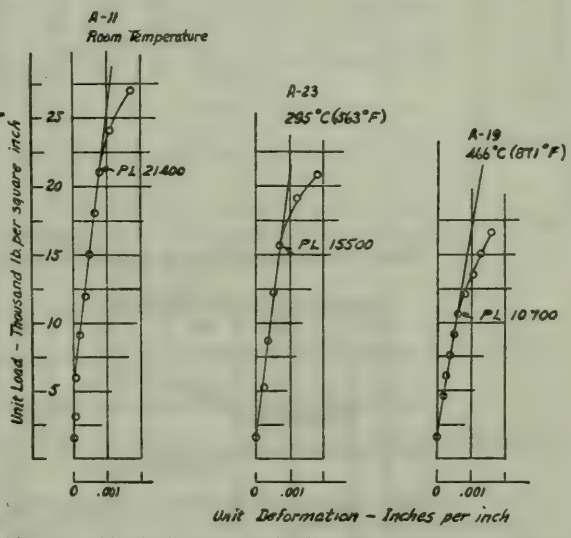
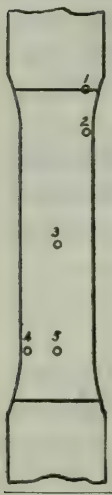


FIG. 9.—*Typical stress-strain diagrams obtained at various temperatures*

Temperature determinations under actual test conditions, made by placing thermocouples in holes located at various points in a specimen carrying entire auxiliary apparatus, show that the position chosen for the single thermocouple (in the fillet) is representative of about the mean of the gradient throughout the gage length,

where the temperature gradually decreased from top to bottom (see Fig. 10 for partial reproduction of these variations). This variation is within 30° C (54° F). It is the greatest in the upper temperature ranges under consideration, and does not exceed 20° C



Desired temperature, degrees Centigrade	Temperature of specimen at positions indicated, degrees Centigrade					Time after couple No. 1 first reached desired temperature, minutes	Average temperature of couples 2, 3, 4, and 5, degrees Centigrade	Maximum temperature variation, degrees Centigrade
	1	2	3	4	5			
165	165	173	167	158	165	15	166	15
320	320	327	327	310	322	0	322	17
	325	334	334	320	329	5	329	14
	325	336	334	318	332	20	330	16
400	402	415	412	393	402	10	405	22
	402	415	412	393	402	20	405	22

FIG. 10.—*Temperatures at various parts of test specimen*

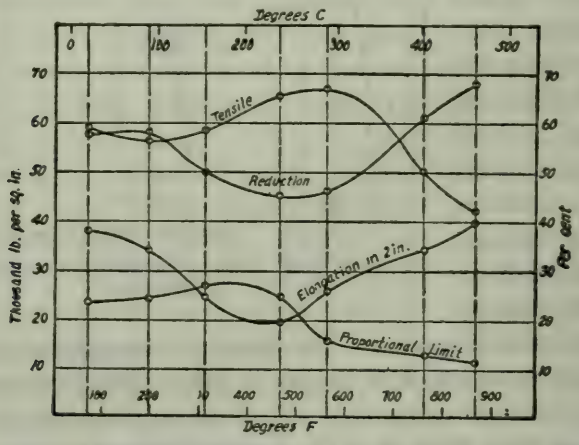


FIG. 11.—*Tensile properties of half-inch A. S. T. M. firebox boiler plate at elevated temperatures (Series 1)*

Plates rated as 52–62 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.19; manganese, 0.43; phosphorus, 0.020; and sulphur, 0.031 per cent.

(36° F) at the lower temperatures used. However, as the thermocouple, specimen with auxiliary apparatus, and furnace are in the same relative position in each test, the results obtained at various temperatures throughout the range 20 to 465° C (70 to 870° F) are comparable.

3. TENSILE PROPERTIES OF HOT-ROLLED BOILER PLATE AT ELEVATED TEMPERATURES

As a basis for comparison with steels subjected to deformation in various ways tensile tests were made on the four grades listed in Table 1. Results obtained are graphically represented in Figures 11, 12, 13, and 14. In all grades of plates increase in temperature above the ordinary atmospheric range is accompanied by distinct changes in strength and ductility, namely:

(*a*) Tensile strength decreases a few thousand pounds per square inch in the neighborhood of 95° C (200° F). This is followed by an increase to a maximum, which occurs at 290° C (550° F) in

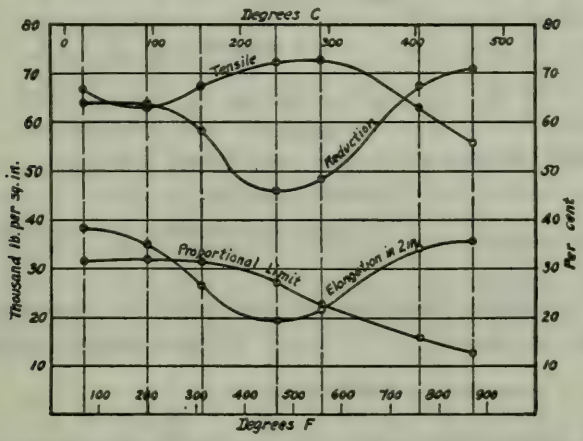


FIG. 12.—*Tensile properties of half-inch marine boiler plate at elevated temperatures (Series 2)*

Plates rated at 60–70 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.25; manganese, 0.38; phosphorus, 0.019; and sulphur, 0.031 per cent.

plates of the first three series and at about 250° C (480° F) in series 4, representing plates of lowest tensile strength. With further increase in temperature the strength decreases, and again approximates ordinary atmospheric temperature values in the range 370 to 400° C (700 to 750° F).

(*b*) The limit of proportionality increases and is a maximum in the neighborhood of 150° C (300° F). In the case of the fire-box grade plates this increase is more marked, and is maintained above room temperature value to a higher temperature than is the case with the marine plate, which has, in effect, constant proportional limit up to about 175° C (350° F). While such differences are noticeable at these relatively low temperatures, the proportional limit of the higher tensile strength marine plate is practically the

same at 465° C (870° F) as that of series 1 and 3 fire-box grade plates and but slightly higher than that of the fourth series (railway fire-box plate of lowest tensile strength).

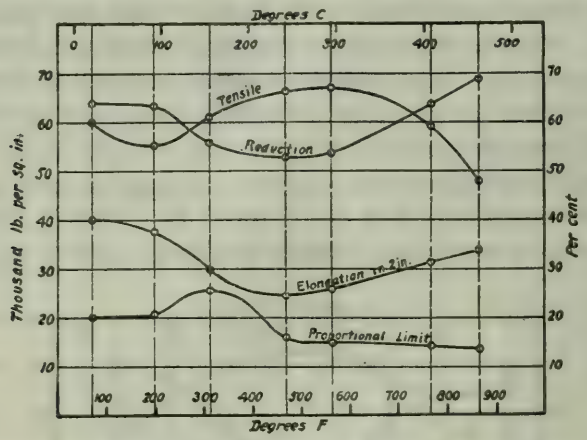


FIG. 13.—*Tensile properties of half-inch railway firebox boiler plate at elevated temperatures (Series 3)*

Plates rated as 45–55 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent.

(*c*) Only a slight decrease in elongation is observed until a temperature of about 95° C (200° F) is reached, above which

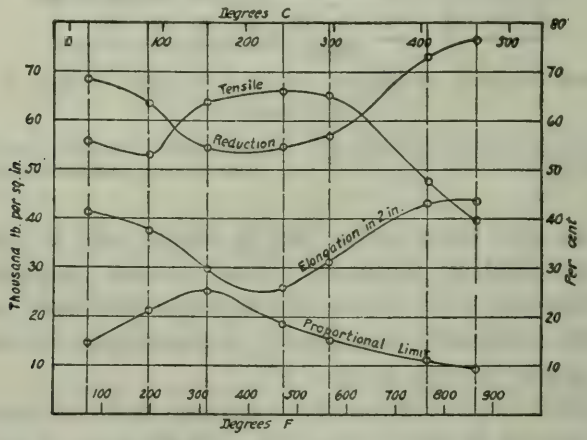


FIG. 14.—*Tensile properties of half-inch railway firebox boiler plate at elevated temperature (Series 4)*

Plates rated as 45–55 000 pounds tensile strength. Tested as rolled. Curves are based on averages of several tests at each temperature chosen. Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent.

the rate of decrease is much higher and a minimum is reached at about 245° C (470° F). Elongation then increases but does not throughout the range under consideration reach the ordinary

atmospheric temperature value in the marine plate (rated 60 000–70 000 pounds tensile strength) and but slightly exceeds its room temperature value in the case of the fourth series at 465° C (870° F).

(*d*) Reduction of area closely follows the inflections registered in the curves for elongation but reaches a minimum at a slightly higher temperature, except in the case of the lowest tensile strength fire-box plate where the minimum occurs at practically the same temperature as that for elongation. At 465° C (870° F) reduction of area is greater than the value obtained at atmospheric temperature in each of the four series of plates tested.

It is to be noted that maximum tensile strength does not coincide with minimum reduction of area or maximum proportional limit, but examination of Figures 11 to 14, inclusive, indicates that the inflections in the curves for reduction of area are, in general, more nearly coincident with the reverse inflections in the curves for tensile strength, and that elongation and proportional limit may be similarly paired.

III. EFFECT OF PERMANENT COLD AND BLUE DEFORMATION ON THE TENSILE PROPERTIES OF STEEL AT VARIOUS TEMPERATURES

1. COLD-ROLLING

The effect of cold work on the tensile properties of steel at ordinary temperatures is to increase the elastic properties and to a smaller degree the tensile strength with an accompanying decrease in ductility as measured by elongation and reduction of area. The greater the total reduction within the capacity of the material the greater is the increase in strength. The tensile properties of steel at elevated temperatures are likewise modified by such cold deformation. Jeffries (33) reports increased strength at blue heat (200 to 300° C) when Armco iron is drawn at room temperature with moderate reductions, but with 96 per cent reduction of area by cold-drawing the tensile strength is greater at room temperature than at any higher one.

The tensile properties at various temperatures of cold-rolled fire-box and marine grades of boiler plate are shown in Figures 15 and 16. Comparison between the cold and hot rolled properties is also shown in Figure 17.

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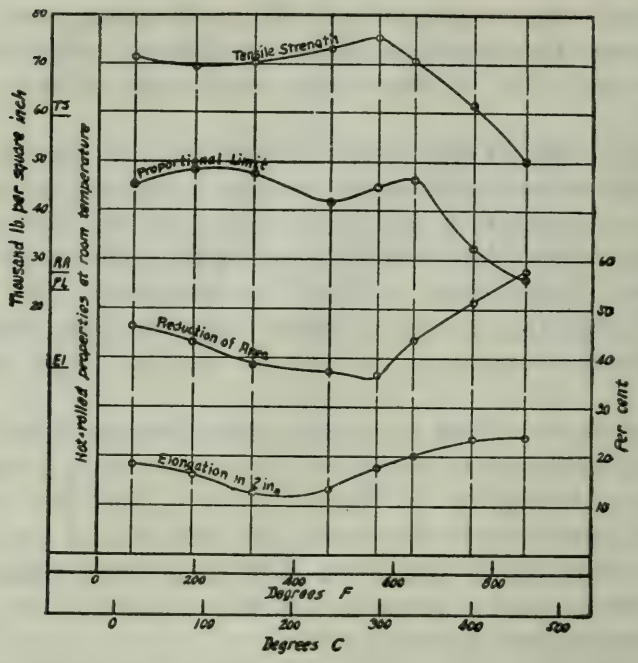

FIG. 15.—*Tensile properties of cold-rolled A. S. T. M. firebox boiler plate at various temperatures (Series 1 steel)*

Carbon, 0.19; manganese, 0.43; phosphorus, 0.020, and sulphur, 0.031 per cent. Plates reduced cold $\frac{1}{16}$ inch from ½ inch thickness

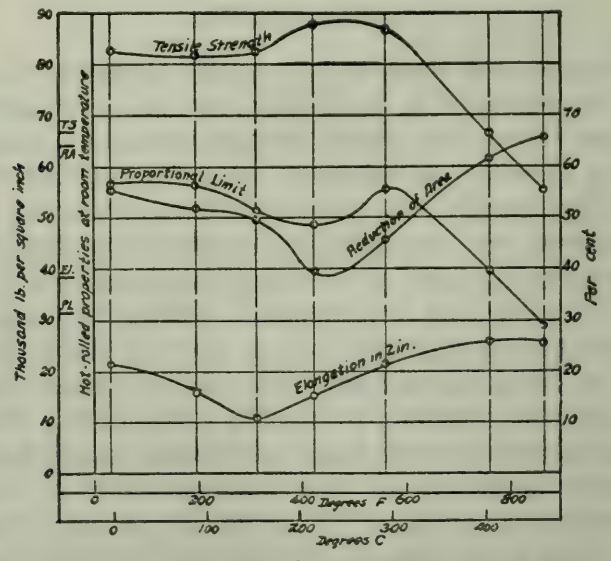

FIG. 16.—*Tensile properties of cold rolled marine boiler plate at various temperatures (Series 2 steel)*

Carbon, 0.25; manganese, 0.38; phosphorus, 0.019; and sulphur, 0.031 per cent. Plates reduced cold, $\frac{1}{16}$ inch from ½ inch thickness.

One-sixteenth inch "cold reduction," approximating 12.5 per cent of the original plate thickness, increases the tensile strength at room temperature about 20 per cent. It also increases the strength of the hot-rolled plates up to about 465° C (870° F) by a similar amount, showing that this effect is maintained until relatively high temperatures are reached.

The changes in proportional limit are more marked and of considerable interest. At ordinary temperatures an increase of about

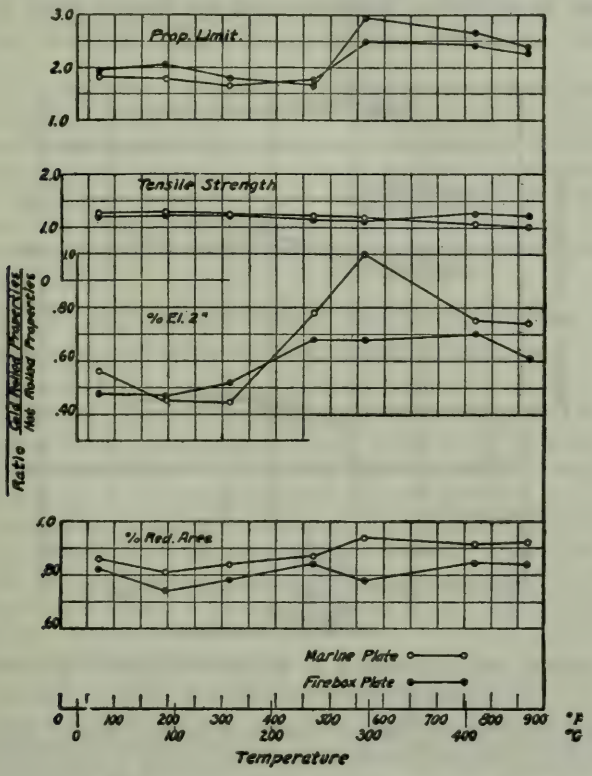

FIG. 17.—*Comparison of tensile properties at various temperatures of cold and hot-rolled firebox and marine boiler plate*

80 to 95 per cent is shown. Similarly, an increase of 60 to 100 per cent above the values obtained in tests of hot-rolled plates is found at temperatures up to and including 245° C (470° F). In the blue-heat range, 295° C (565° F), the increase in proportional limit due to cold work reaches the very high value of 150 per cent in the marine plate and nearly 200 per cent in the fire-box grade. This, however, is not accomplished at the expense of ductility, as the relation between elongation of cold and hot rolled plates has also increased. The relation between reduction of area of cold

and hot finished marine steel has likewise increased to some extent, while that for the fire-box grade has decreased but slightly.

Bregowsky and Spring (25) in a report of tests of cold-rolled Bessemer shafting show secondary inflections in their tensile properties—temperature curves similar to those described above though occurring at somewhat lower temperatures. However, no direct comparison with the hot-rolled steel is available.

In order to determine whether these changes at blue heat are maintained at ordinary temperatures specimens were annealed at successively increasing temperatures and then tested in the usual

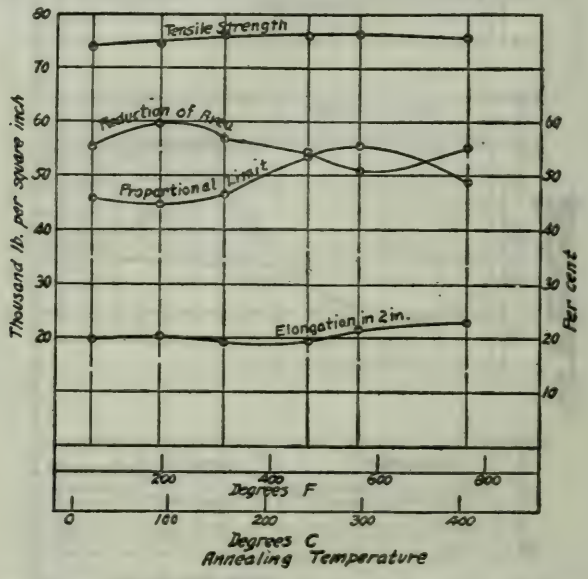

FIG. 18.—*Effect of partial annealing on the tensile properties of cold-rolled railway firebox boiler plate (Series 4 steel)*

Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent. Plates reduced cold, $\frac{1}{16}$ inch from $\frac{1}{4}$ inch thickness. Held 30 minutes at annealing temperature and air cooled.

manner at the temperature of the room. The results, which are graphically represented in Figure 18, illustrate, as far as the tensile properties are concerned, the benefits derived from the "bluing" of cold-finished products, such as thin-wall seamless steel tubes, and show the effects of final partial annealing on low-carbon steel cold rolled in the ordinary manner. Short-time annealing in the blue-heat range, 295° C (565° F), has little effect on the tensile strength and elongation but materially increases the elastic ratio with only a minor decrease in reduction of area.

In the case of the fire-box steel under test this increase in the limit of proportionality is about 20 per cent. It is likewise

apparent from Figure 18 that a short time annealing at somewhat higher temperature, 405° C (765° F), accomplishes little, if anything, in the improvement of the tensile properties of this cold-rolled steel.

2. BLUE ROLLING

Working steel in the ranges where ordinarily temper colors are obtained has long been considered deleterious and even dangerous. Stromeyer (37) warns against such practice and, in referring to his series of tensile and bending tests on iron, mild and hard steels, writes:

> All these results point unmistakably to the great danger which is incurred if iron or steel is worked at a blue heat. * * * It is very common practice amongst boiler makers to "take the chill out of the plate" if it requires a little setting, or to set a flanged plate before it is cold. This is really nothing else than working it at a blue heat and should not be allowed. * * * All hammering or bending of iron and steel should be avoided, unless the metals are either cold or red-hot. Where this is impossible and where the plate or bar has not broken while blue-hot, it should be subsequently annealed.

Howe (38) in 1891 summarized available information relating to what he calls "blue shortness" and states in part:

> Not only are wrought iron and steel much more brittle at a blue heat[6] than in the cold or at redness, but, while they are probably not seriously affected by simple exposure to blueness, even if prolonged, yet if they be worked in this range of temperature they remain extremely brittle after cooling and may indeed be more brittle then than while at blueness. This last point, however, is not certain.
>
> The loss of ductility as measured by endurance of bending and drifting is enormous. That this is not due to incipient cracks is shown by the simultaneous increase of tensile strength and by the restoration of ductility by annealing. The effect of blue working on ductility as measured by elongation (on rupture by static tensile stress) is very irregular and apparently anomalous. * * * Heating to redness may completely remove the effects of blue working.

Howe further called attention to the resemblance between the effects of cold working and those of blue working, and that the immediate effect of these two operations might be suspected to be identical in nature. He states:

> It is true that the gain in elastic limit does not seem to excel that in tensile strength as markedly in the case of blue as in the case of cold working, nor is it clear that the tensile strength and elastic limit increase during rest after blue as they do after cold working. But this is natural, for we see reason to believe that heating cold-worked iron to blueness greatly accelerated the changes which cold working starts, so that, when this change is started by distortion at blueness instead of in the cold it may occur so rapidly and so nearly reach its full growth before the metal grows cold that no considerable further change occurs thereafter. The effects of blue working are more intense and more injurious than those of cold working.

[6] The terms "blue work," "blue shortness," etc., as used by Howe, refer to temperatures where ordinarily temper colors are obtained and may be considered to be within the range 220–320° C (430–600° F).

Ridsdale (40) referred to blue heat, 315–370° C (600–700° F), as the state of minimum plasticity and showed that soft steel developed brittleness when worked or soaked in a furnace for a long time in this range. He further pointed out that by reheating to a suitable temperature the good qualities of such steel were restored.

Kurzwernhart (39) reported that a brittle boiler plate returned to the Teplitz Steel Works gave rise to investigation showing that the plate had been removed from the furnace at an uneven temperture extending from red-hot on one side to brown-hot on the other. Experiments showed that not only was the blue heat dangerous, but working the metal at certain other temperatures was likewise deleterious. Bending tests showed the most dangerous temperature to be that at which the surface assumed a light yellowish coloration. Blue brittleness could be removed, however, by heating to a dull red such as could only be observed in a darkened room.

Jeffries (34) has studied the effects of blue work on the tensile properties of Armco iron and reached the following conclusions:

1. Armco iron deformed at room temperature a given amount does not increase as much in tensile strength as when deformed the same amount at blue heat.

2. The effect of drawing Armco iron at 200 to 400° C is to produce greater tensile strength at all temperatures up to 550° C than would obtain with the same amount of deformation in the cold. The elongation is less after drawing at 200 to 400° C than after drawing at room temperature. The same conclusion is true, in general, of the reduction of area.

Jeffries also reports results obtained in private communication from W. E. Ruder to show the effects of rolling cold and at various elevated temperatures on the strengths of mild steel and annealed nickel-chromium steel. These data are reproduced, respectively, in Tables 3 and 4.

TABLE 3.—Tensile Strength of Mild Steel Drawn at Various Temperatures [1]

Size and condition of material	Tensile strength	Size and condition of material	Tensile strength
	Lbs./in.²		Lbs./in.²
0.192 inch diameter	58 200	0.192 inch diameter	112 700
Annealed	55 200	Reduced to 0.179 inch at 300° C	113 500
0.192 inch diameter	67 000	0.192 inch diameter	114 100
Reduced to 0.179 inch cold	69 500	Reduced to 0.179 inch at 400° C	105 300
0.192 inch diameter	110 200		
Reduced to 0.179 inch at 240° C	112 300		

[1] Zay Jeffries, Physical changes in iron and steel below the thermal critical range, Mining and Metallurgy, 158 (1920), section No. 20.

TABLE 4.—Tensile Properties of a Nickel-Chromium Steel Heat-Treated and Worked in Different Ways [1]

Condition of material	Tensile strength	Yield point	Percentage elongation in 2 inches
	Lbs./in.²	Lbs./in.²	
Annealed	101 500	67 100	25.5
Annealed, then reduced 10 per cent at 300° C	137 600	132 500	10.5
Heat treated and reduced 10 per cent at 300° C	199 100	163 700	7.5
Annealed and reduced 10 per cent cold	114 200	102 000	19.5

[1] Zay Jeffries, Physical changes in iron and steel below the thermal critical range, Mining and Metallurgy, 158 (1920), section No. 20.

While there seems to be unanimity of opinion that blue work is deleterious to steel, Howe (38) early called attention to the fact that—

> Millions of car axles, blue from "hot boxes," are chilled with snow and jarred under heavy load at loose rail joints, yet are apparently unharmed. Among the many thousand steel boilers tens of thousands of plates must have been worked more or less at blueness, yet failures are rare * * *. Again, though many recognize that machine riveting has a great advantage over hand riveting, in that its work ceases before the rivet cools to blueness, while the hand riveter usually continues hammering while the rivet is passing blueness, yet relatively few hand worked rivets fail in use * * *. Finally, much crucible steel in the form of bars, plates, etc., is habitually rolled or hammered till its temperature has fallen below visible redness.

More recently the question of effects of deformation at temperatures below the thermal transformations has become of interest in connection with the straightening of crank shafts for airplane engines while cooling from the tempering heat. Whether such work is detrimental or can safely be applied to these and other types of forgings has for some little time been under discussion.

In order to determine the effect of permanent deformation at blue heat on the high-temperature properties of boiler plate several patterns were reduced at about 300° C from $\frac{1}{2}$ inch to $\frac{15}{32}$ and $\frac{7}{16}$ inch, respresenting, respectively, 6.25 and 12.5 per cent reduction in thickness. The patterns were rolled in a single-stand 16-inch mill, a number of light reductions to effect the totals mentioned above being used. Considerable difficulty was encountered at first in producing flat plates suitable for test; probably, in the main, because of the short length of the patterns. An attempt was made to straighten the first plates cold and also at blue heat immediately after rolling, but they broke transversely with a very coarsely crystalline fracture as soon as pressure was applied.

It was found after discarding these plates that all the patterns of series 1 and 2 steels had been used, so that it was necessary to carry out the desired tests on series 4, railway fire-box steel, quite similar in composition and properties to series 3. This, however, does not affect consideration of the relative effects of blue and cold work as shown in Table 5 based on data represented graphically in Figures 17 and 19.

TABLE 5.—Effect of Blue and Cold Rolling on the Tensile Properties of Fire Box Boiler Plate at Various Temperatures

Temperature of tests					Hot-rolled (series 1)	1/16-inch "cold reduction"	Ratio [1]	Hot-rolled (series 4)	1/32-inch "blue reduction"	Ratio [1]	1/16-inch "blue reduction"	Ratio [1]
Hot rolled steel	Cold rolled steel	Blue rolled steel	Average									
					Tensile strength, pounds per square inch							
°C	°C	°C	°C	°F								
21	21	21	21	70	59 000	71 130	1.21	55 600	72 000	1.29	79 800	1.43
91	89	91	90	194	55 530	69 300	1.25	52 800	68 900	1.30	77 700	1.47
156	156	156	156	313	58 100	70 100	1.21	63 800	69 400	1.09	78 300	1.23
243	243	243	243	469	65 130	72 930	1.12	65 800	74 300	1.13	79 100	1.20
295	295	295	295	563	66 700	75 540	1.13	65 200	73 650	1.13	78 000	1.20
407	402	407	405	761	49 150	61 850	1.26	47 800	53 850	1.12	57 700	1.21
465	463	463	463	865	41 850	50 400	1.20	39 900	43 600	1.09	44 400	1.11
					Proportional limit, pounds per square inch							
21	21	21	21	70	23 300	45 130	1.94	14 500	42 800	2.95	53 500	3.69
91	89	91	90	194	23 630	48 550	2.05	21 200	52 500	2.48	60 200	2.84
156	156	156	156	313	26 600	47 450	1.78	25 100	48 350	1.93	58 800	2.34
243	243	243	243	469	24 900	41 700	1.67	18 500	48 500	2.62	57 200	3.09
295	295	295	295	563	15 250	44 630	2.92	15 000	34 200	2.28	54 800	3.65
407	402	407	405	761	12 960	32 000	2.66	11 500	29 650	2.58	40 200	3.50
465	463	463	463	865	11 430	26 050	2.36	9 400	22 750	2.42	27 400	2.92
					Percentage elongation in 2 inches							
21	21	21	21	70	37.8	18.2	0.48	41.0	22.2	0.54	18.0	0.44
91	89	91	90	194	34.7	16.4	.47	37.5	17.5	.47	15.1	.40
156	156	156	156	313	24.9	12.8	.52	29.6	17.3	.58	13.3	.45
243	243	243	243	469	19.9	13.4	.68	25.8	18.2	.70	15.1	.58
295	295	295	295	563	25.7	17.5	.68	31.0	25.0	.81	16.4	.53
407	402	407	405	761	33.8	23.6	.70	43.0	32.8	.76	25.8	.60
465	463	463	463	865	39.2	23.8	.61	43.5	34.2	.79	27.9	.64
					Percentage reduction of area							
21	21	21	21	70	57.1	46.7	0.82	68.2	50.7	0.74	46.2	0.68
91	89	91	90	194	58.3	43.2	.74	63.4	47.7	.75	43.4	.68
156	156	156	156	313	49.3	38.6	.78	54.3	41.0	.75	37.3	.69
243	243	243	243	469	45.1	37.3	.84	54.7	41.2	.75	36.3	.66
295	295	295	295	563	45.6	36.5	.78	56.8	46.6	.82	42.6	.75
407	402	407	405	761	60.7	51.2	.84	73.0	62.4	.85	57.5	.79
465	463	463	463	865	67.7	57.2	.84	76.8	66.0	.86	63.6	.83

[1] In each case the ratio given is the blue or cold rolled properties to the hot-rolled properties as determined by tests on patterns of the same plate.

1. The increase in strength at room temperature resulting from "cold reduction" of 12.5 per cent is about the same as that produced by half this reduction (6.25 per cent) at blue heat.

This, in general, is also true at temperatures up to 295° C (565° F) (blue heat). Above this temperature the increase in strength resulting from "blue deformation" is somewhat less than that from cold rolling.

2. A "blue reduction" of twice the amount given above (6.25 per cent) does not increase the strength at room or elevated temperatures proportionally.

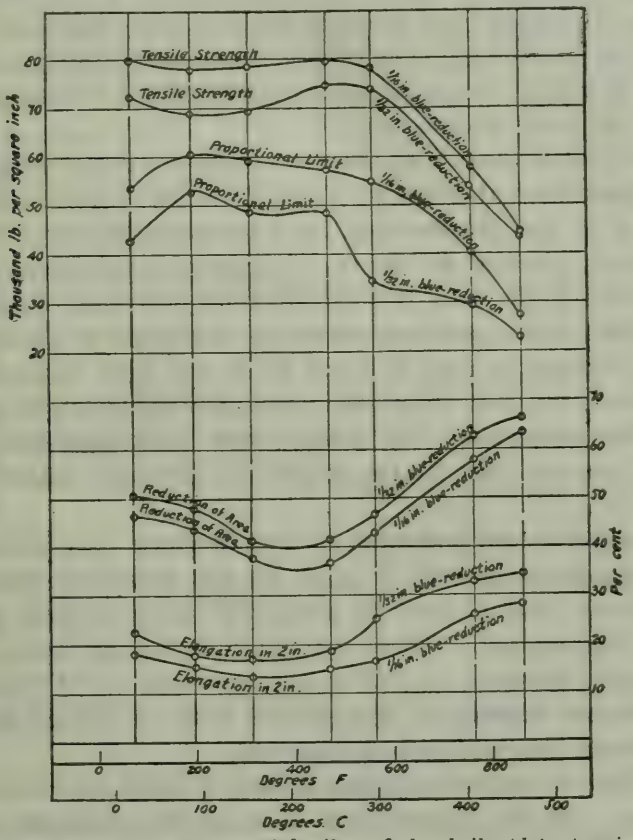

FIG. 19.—*Tensile properties of blue-rolled railway firebox boiler plate at various temperatures (Series 4 steel)*

Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent. Plates reduced at about 300° C from ½ inch thickness.

3. At 245° C (470° F) the strength of the blue worked steel is little in excess of that hot rolled and about the same whether the "blue reduction" is 6.25 or 12.5 per cent.

4. The maximum tensile strength of the steel subjected to 6.25 per cent "blue reduction" is obtained at blue heat, 295° C (565° F), and the shape of the tensile strength temperature curve shown in Figure 19 is similar to that for the cold-rolled

steel, while with twice this "blue reduction" (12.5 per cent) about the same strength is obtained at 295° C (565° F) as at room temperature. In both cases, however, the tensile strength temperature curves change direction quite abruptly at or about 295° C (565° F).

5. The increase in the limit of proportionality at room temperature resulting from 6.25 per cent "blue reduction" is greater than that obtained from twice as much "cold reduction." This is also true up to 245° C (470° F), above which temperature the increase resulting from cold work is about equal to that produced by the blue work in question.

6. The proportional limit increases with first rise in temperature and is a maximum at about 90° C (195° F), after which it decreases. The form of the proportional limit temperature curve for steel reduced 6.25 per cent at blue heat is similar to that reduced twice this amount in the cold, but the secondary increase which in the cold worked steel appears to attain its maximum at about 340° C (645° F) occurs at 245° C (470° F) in the blue worked metal. This inflection is not observed in the steel subjected to 12.5 per cent "blue reduction," the proportional limit decreasing slowly from 90 to about 245° C (195 to 470° F) and more rapidly thereafter.

7. Elongation and reduction of area decrease to a minimum in the neighborhood of 200° C (410° F) and thereafter increase to high values at 465° C (870° F) greatly in excess of those obtained at room temperature. There appears to be a more rapid increase in elongation between 295 and 410° C (565 and 770° F) coincident with the rapid decrease of proportional limit mentioned above for steel reduced 6.25 per cent at blue heat.

The effect of partial annealing of blue worked steel is shown in Figure 20. As the temperature increases the strength at room temperature decreases, and this is accompanied by increase in elongation and reduction of area. The proportional limit decreases until an annealing temperature of about 500° C (930° F) is reached, but with slow cooling from above this to about 600° C (1110° F) the elastic ratio is greatly increased. Annealing for 30 minutes at about 730° C (1345° F) completely removes the effects of "blue deformation."

3. DEPTH OF PENETRATION OF EFFECT OF BLUE AND COLD ROLLING.

Since the effects of blue and cold work are so marked and maintained over a considerable temperature range, the question naturally arises as to whether the increased strength of the plate is due to hardening of the "skin," so that there is a decrease in strength from surface to center or whether the magnitude of the observed effect is substantially the same throughout the cross section, especially in light plates such as are under investigation. The surfaces of cold and blue rolled bars were accordingly milled to progressively increasing depths and tested in the usual manner at room temperature.

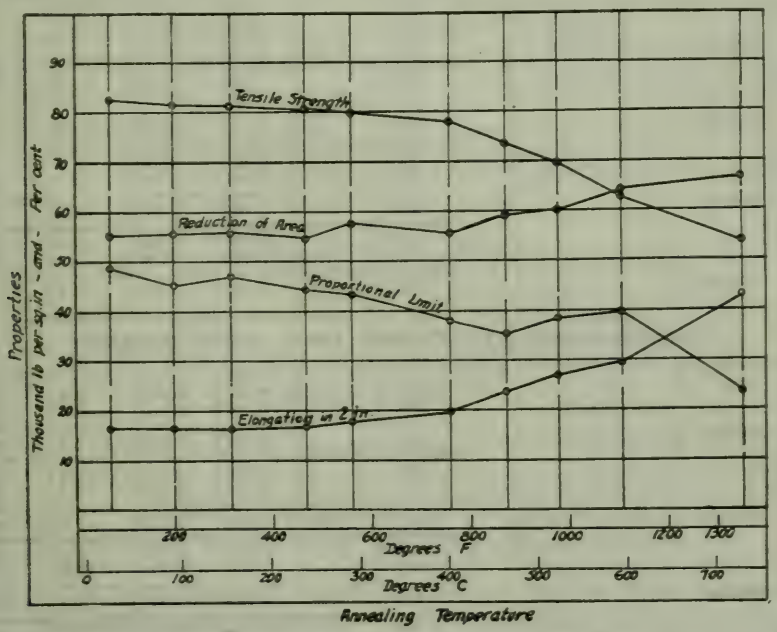

FIG. 20.—*Effect of partial annealing on the tensile properties of blue-rolled railway fire-box boiler plate (Series 3 steel)*

Carbon, 0.17; manganese, 0.36; phosphorus, 0.024; and sulphur, 0.031 per cent. Reduced 1/32 inch at about 300° C from ¼ inch thickness. Held 30 minutes at annealing temperatures and air cooled.

The results of these tests are given in Table 6 and show that there is substantially no difference in the strength factors when even a considerable depth of surface metal has been removed, whereas the ductility as measured by elongation and reduction of area gradually decreases with removal of increasing layers of metal. The origin of this effect is, without doubt, due to the decrease

in thickness of the specimen, while the width has been kept constant.[7]

TABLE 6.—Tensile Properties of Cold and Blue Rolled Fire-Box Boiler Plate upon Removing Successively Increasing Depths of Surface Metal (Series 3 steel)

REDUCED 1/16-INCH COLD FROM 1/2-INCH THICKNESS

Sample number	Sample thickness	Surface metal removed	Proportional limit	Tensile strength	Percentage elongation in 2 inches	Percentage reduction of area
	Inch	Inch	Lbs./in.²	Lbs./in.²		
E 13	0.437	.....	52 000	82 200	18.5	47.4
E 20	.437	.....	47 200	74 800	18.5	47.1
Average	.437	.....	49 600	78 500	18.5	47.2
E 14	.377	.....	54 500	74 900	18.0	46.9
E 19	.371	.....	56 500	78 600	17.0	41.2
Average	.374	0.031	55 500	76 750	17.5	44.0
E 18	.317	.....	54 000	76 400	15.5	44.3
E 15	.310	.....	53 000	76 000	17.0	41.5
Average	.313	.062	53 500	76 200	16.2	42.9
E 25	.250	.....	56 000	77 300	14.0	39.8
E 11	.252	.....	59 000	76 500	13.0	40.0
Average	.251	.093	57 500	76 900	13.5	39.9
E 21	.188	.....	53 500	77 900	14.5	36.8
E 16	.192	.....	53 500	77 500	13.0	34.5
Average	.190	.124	53 500	77 700	13.8	35.6

REDUCED 1/16-INCH AT BLUE HEAT FROM 1/2-INCH THICKNESS

P 3	0.438	.....	70 000	94 600	13.0	33.7
P 9	.442	.....	69 500	94 300	12.5	38.6
Average	.440	.....	69 750	94 450	12.8	36.2
P 11	.377	.....	70 000	94 700	11.5	38.2
P 10	.375	.....	66 000	95 600	10.5	35.3
Average	.376	.032	68 000	95 150	11.0	36.8
P 8	.311	.....	68 500	95 700	9.5	36.0
P 4	.311	.....	70 000	95 700	10.5	36.6
Average	.311	.064	69 250	95 700	10.0	36.3
P 12	.249	.....	66 000	95 200	9.0	32.0
P 13	.250	.....	73 000	94 800	8.0	31.2
Average	.250	.095	69 500	95 000	8.5	31.6
P 2	.185	.....	71 000	96 400	6.5	22.4
P 1	.185	.....	70 000	96 400	6.5	23.0
Average	.185	.128	70 500	96 400	6.5	22.7

4. TENSILE TESTS OF TRANSVERSE SPECIMENS OF HOT, COLD, AND BLUE ROLLED BOILER PLATE AT VARIOUS TEMPERATURES

Tests of longitudinal specimens taken from plates rolled at various temperatures do not fully define the effects of such work even when only considering the tensile properties. Accordingly

[7] H. L. Moore, Tension tests of steel with test specimens of various size and form. Report of subcommittee to Committee E 1, Proc. Am. Soc. Test. Mat. 1918, part 1, p. 403.

tests were made on samples taken transversely from hot, cold, and blue rolled fire-box steel, series 4, Table 1. The results are given in Figure 21 and summarized to show the high temperature comparisons in Table 7.

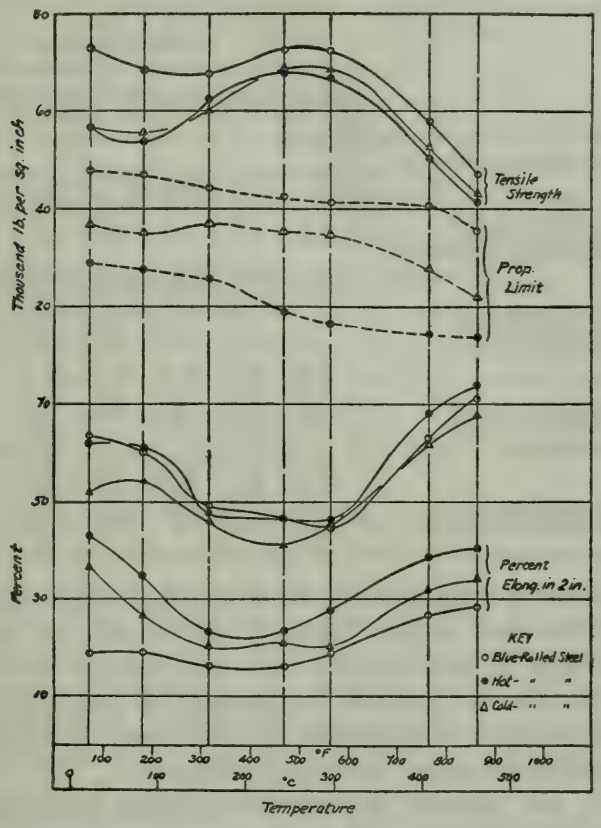

FIG. 21.—*Tensile properties of hot-, cold-, and blue-rolled railway firebox boiler plate at various temperatures as determined on transverse test specimens (Series 4 steel)*

Carbon, 0.18; manganese, 0.43; phosphorus, 0.017; and sulphur, 0.035 per cent. Cold- and blue-rolled plates reduced $\frac{1}{16}$ inch from $\frac{1}{4}$ inch thickness, respectively, at room temperature and at about 300 C°.

It is at once evident that the general form of the tensile properties temperature curves is similar to those for longitudinal tests, with the exception of the limit of proportionality, which does not increase with the first rise in temperature. In general, the first changes are slight, but there is a decrease in hot and cold rolled steel, while in that rolled at blue heat there is a decided tendency for the limit of proportionality to remain at nearly its room temperature value over a considerable range. The agreement between duplicate determinations of this factor at slightly elevated temperatures is not so good as that obtained under similar conditions

in longitudinal samples, so that the values will be considered as tentative, and in Fig. 21 are shown as dotted lines.

TABLE 7.—Comparison of Tensile Properties at Elevated Temperatures of Hot, Cold, and Blue Rolled Fire-Box Boiler Plates as Determined on Transverse Test Specimens (Series 4 Steel)

	Temperature of test.						
	21° C (70° F)	92° C (198° F)	156° C (313° F)	243° C (469° F)	295° C (563° F)	407° C (764° F)	463° C (865° F)
Proportional limit, pounds per square inch:							
Hot rolled	28 850	27 250	25 500	18 600	16 400	14 200	13 500
Cold rolled	37 000	34 700	36 900	34 700	34 500	27 500	21 400
Blue rolled	47 500	74 000	44 000	42 350	41 000	40 450	35 000
Ratio of cold rolled to hot rolled	1. 28	1. 27	1. 44	1. 87	2. 10	1. 94	1. 59
Ratio of blue rolled to hot rolled	1. 65	1. 72	1. 72	2. 28	2. 50	2. 74	2. 59
Tensile strength, pounds per square inch:							
Hot rolled	56 700	53 300	62 350	67 400	66 900	50 000	41 100
Cold rolled	56 900	55 500	60 000	68 400	68 500	52 700	42 400
Blue rolled	72 750	68 150	67 250	72 300	72 250	57 700	46 500
Ratio of cold rolled to hot rolled	1. 00	1. 04	. 96	1. 02	1. 02	1. 06	1. 03
Ratio of blue rolled to hot rolled	1. 28	1. 29	1. 08	1. 08	1. 08	1. 15	1. 13
Percentage of elongation in 2 inches:							
Hot rolled	42. 8	34. 8	23. 2	23. 3	27. 3	38. 5	40. 2
Cold rolled	36. 5	26. 5	20. 6	21. 0	19. 8	31. 8	33. 7
Blue rolled	18. 5	19. 0	16. 2	16. 2	18. 8	26. 5	28. 2
Ratio of cold rolled to hot rolled	. 85	. 76	. 89	. 90	. 72	. 82	. 84
Ratio of blue rolled to hot rolled	. 43	. 55	. 70	. 69	. 69	. 69	. 70
Percentage reduction of area:							
Hot rolled	62. 1	61. 3	47. 8	46. 4	46. 3	67. 7	73. 6
Cold rolled	63. 7	60. 3	49. 2	46. 7	44. 7	62. 8	70. 9
Blue rolled	52. 2	54. 9	46. 2	41. 0	45. 6	61. 3	67. 8
Ratio of cold rolled to hot rolled	1. 02	. 98	1. 03	1. 00	. 96	. 93	. 96
Ratio of blue rolled to hot rolled	. 84	. 90	. 97	. 88	. 98	. 91	. 92

The increase in transverse tensile strength at room temperature resulting from blue or cold rolling is very much less than that observed in longitudinal tests for the same mechanical reductions. However, the relation between the strength of blue, cold, and hot rolled steel at room temperature is maintained throughout the entire temperature range under consideration.

Similarly, the increase in proportional limit and decrease in ductility resulting from deformation at room temperature or blue heat are less than the effects observed in longitudinal tests, but the ratio of limit of proportionality of cold or blue rolled steel to that of the hot rolled metal is greater at blue heat than at room temperature.

The proportional limit of steel deformed cold or at blue heat is raised more than is the transverse strength, but this difference is not so marked as in the case of tests made of longitudinal samples.

5. PERMANENT DEFORMATION PRODUCED BY STRETCHING

Huston (42) found that in loading bridge iron to just above the "so-called elastic limit" the ductility or toughness remained unaffected, so that the metal would yield with every small increase

in load, while when stressed just below the iron became rigid and would not elongate without decided load increase.

From a large number of tests of wrought iron and low-carbon steel Bauschinger (43) made certain empirical deductions regarding the behavior of proportional limit and yield point when such metals were subjected to overstrain at ordinary temperatures. Among these deductions were the following:

He found that when stretching was produced by a load between the proportional limit and yield point the former was raised, whereas an applied stress above the yield point resulted in a decrease in the limit of proportionality. Upon aging for a long time at room temperature or for shorter periods at higher temperatures elevation of this factor was produced.

Raised proportional limit and yield point brought about by aging subsequent to overstrain were again lowered by high heating, but the method of cooling was observed to play an important part. Rapid cooling was more effective in lowering these factors than slow cooling, but the time of rest after heating and cooling exerted no further effect.

Howe (38) reported that stretching at room temperature lowered the limit of proportionality of steel, often to zero, so that if retested immediately no proportional limit or a very low one was found. The effect of rest was to slowly restore the elasticity and finally raise it above the load that caused the previous deformation, but this occurred more slowly at room temperature than when the steel was warmed. While Howe's statements are not in entire agreement with the work of Bauschinger, his results appear consistent with the tests reported by the latter.

Muir (44) found that the elastic recovery of overstrained steel was as marked after three or four minutes at 100° C (212° F) as in two weeks at room temperature and was impeded or entirely prevented at lower temperatures around 0° C (32° F).

Howard (8) stated that "the effect of straining hot on the subsequent strength when tested cold appears to depend upon the magnitude of the straining force and the temperature when overstrained. There is a zone of temperature in which the effect of hot straining elevates the elastic limit above the applied stress and above the primitive value, and if the straining force approaches the present tensile strength there results a material elevation of that value when cooled. After exposure to higher temperatures a gradual loss occurs in both elastic limits and tensile strength, and generally there follows a noticeable increase in the contrac-

TABLE 8.—Experiments Showing Some Effects of Tensional Elastic Overstrain at Various Temperatures on the Tensile Properties of Fire-Box Boiler Plate (Series 1 Steel)

Sample number	Treatment	Proportional limit	At temperature	Sustained load: Pounds per square inch	Sustained load: Pounds per square inch overload	Sustained load: Time maintained	Sustained load: At temperature	Aging: Time	Aging: At temperature	Final tensile properties: Proportional limit	Final tensile properties: Tensile strength	Final tensile properties: Per cent elongation in [2] inches	Final tensile properties: Per cent reduction of area	Final tensile properties: At temperature
		Lbs./in.²	°C			Minutes	°C	Minutes	°C	Lbs./in.²	Lbs./in.²			°C
J 9	Single overload at room temperature.	30 300	Room.	39 650	9 350	5	Room.	5	Room.	35 700	58 700	39.0	48.1	Room.
J 10		30 600	Room.	40 000	9 400	5	Room.	5	Room.	Very low.	58 450	42.0	48.8	Room.
J 16		24 000	Room.	40 000	16 000	5	Room.	[1] 5	Room.	37 000	58 100	42.0	47.7	Room.
H 26	Single overload at 295° C for various periods and different times at rest	13 500	295	30 000	17 500	5	295	5	295	28 000	65 900	23.5	41.5	295
H 20		.....	295	16 250	.....	44	295	45	295	17 800	65 800	24.8	35.2	295
H 22		.....	295	16 250	.....	42	295	8	295	17 100	66 000	24.8	42.6	295
H 24	Repeated overload at 295° C....	15 500	295	16 250	750	5	295	5	295	.....	.....	.....	.....	.....
	After 15 repetitions at 16 250 pounds	.....	.....	.....	.....	.....	.....	.....	.....	16 400	64 300	27.0	41.5	295
H 25	Repeated and increasing overload at 295° C	15 000	295	16 250	1 250	5	295	5	295	.....	.....	.....	.....	.....
		17 700	295	22 680	7 680	5	295	5	295	.....	.....	.....	.....	.....
		22 000	295	25 920	10 920	5	295	5	295	.....	.....	.....	.....	.....
		24 800	295	29 160	14 160	5	295	5	295	.....	.....	.....	.....	.....
		27 700	295	30 780	15 780	5	295	5	295	.....	.....	.....	.....	.....
		30 600	295	34 000	19 000	5	295	5	295	.....	.....	.....	.....	.....
		33 000	295	35 600	20 600	5	295	5	295	.....	.....	.....	.....	.....
		[2] 35 500	295	37 200	22 200	5	295	5	295	.....	.....	.....	.....	.....
		35 000	295	40 500	25 500	5	295	5	295	.....	.....	.....	.....	.....
		39 900	295	43 740	28 740	5	295	5	295	.....	.....	.....	.....	.....
		40 000	295	42 120	27 120	5	295	5	295	.....	.....	.....	.....	.....
		40 500	295	45 360	30 360	5	295	5	295	.....	.....	.....	.....	.....
		45 000	295	46 980	31 980	5	295	5	295	.....	.....	.....	.....	.....
		45 500	295	48 600	33 600	5	295	5	295	.....	.....	.....	.....	.....
		47 500	295	50 220	35 220	5	295	5	295	.....	.....	.....	.....	.....
		49 000	295	57 840	36 840	5	295	5	295	.....	.....	.....	.....	.....
		50 500	295	53 460	38 460	5	295	5	295	.....	.....	.....	.....	.....
		51 000	295	55 080	40 080	5	295	5	295	.....	.....	.....	.....	.....

		52 750	295	56 700	41 700	5	295	5	295	.....	.....	.....	.....	.....
		55 000	295	58 940	43 940	5	295	5	295	.....	.....	.....	.....	.....
		53 500	295	63 180	48 180	5	295	5	295	.....	.....	.....	.....	.....
		56 000	295	64 800	49 800	5	295	5	295	56 250	66 340	26. 8	40. 3	295
H 21	Single overload at 407° C	.....	407	13 960	.....	[2] 4	407	43	407	13 400	50 450	37. 3	59. 9	407
H 23		.....	407	13 960	.....	45	407	5	407	15 750	53 300	34. 8	54. 3	407
J 11	Single overload at 463° C	16 600	463	31 400	14 800	5	463	5	463	15 500	44 300	35. 0	64. 3	463
J 17		16 600	463	25 000	[3] 8 400	5	463	5	463	23 000	43 600	39. 0	63. 0	463
J 23	Effect overload at 295° C on room temperature properties.	.....	.....	32 900	.....	5	295	([4])	([4])	Very low.	58 600	35. 0	47. 0	Room.
J 15	Effect of long rest on J 23	.....	.....	30 000	.....	5	463	([5])	([5])	36 500	59 100	32. 5	48. 0	Room.
J21	Effect of overload at 465 ° C on room temperature properties	.....	.....	25 000	.....	5	463	([6])	([6])	No curves.	58 450	37. 5	48. 1	Room.
J20		.....	.....	25 160	.....	5	463				59 200	38. 5	48. 7	Room.
J18	Effect of long rest on J20	.....	.....	25 000	.....	5	463	([7])	([7])	35 500	59 600	39. 0	48. 7	Room.
J 19	Effect of normalizing on recently overloaded steel	.....	.....	30 000	.....	5	295	([8])	([8])	32 000	58 250	40. 5	50. 7	Room.

[1] At 1,550 pounds per square inch.
[2] Cooled while resting overnight. Then reheated.
[3] Approximate value.
[4] Cooled 1 hour to room temperature.
[5] Cooled; then 46 2/3 hours at room temperature.
[6] Cooled in 30–40 minutes to room temperature.
[7] Cooled, then 45 1/6 hours' rest at room temperature.
[8] Cooled 3 minutes, normalized 843° C cooled 2½ hours to room temperature.

tion of area." Howard found the zone of elevation of the elastic limit had apparently been passed when the steel was subjected to overstrain at about 395 to 425° C (740 to 800° F) and noted the importance of time between overload at high temperatures and subsequent test.

Because of the extended field for research along these lines, as pointed out by Howard (8), Jeffries (34), and others, and because of the character and purpose of this investigation, the tests of overstrained steel made by the author were limited and undertaken with the view that the results might show some differences in deformational characteristics of steel above and at or below blue heat, for the most marked changes in tensile properties have been found in this temperature range. No generalizations are made from the data obtained in view of the omission of yield point determinations, but attention is drawn to certain of the observed effects shown in Table 8.

At blue heat, 295° C (565° F), tensional stress in excess of the limit of proportionality raises this factor in a short time after release of load to a value approximating the stress producing the previous deformation, but when this stretching at blue heat is followed by cooling to room temperature and subsequent test the immediate effect of the "blue overstrain" is a lowering of the proportional limit. This also appears to be the case at 465° C (870° F).

Repeated overstrain at blue heat, whether at constant or increasing loads, raises the apparent limit of proportionality at this temperature in a like manner and to a similar degree. The magnitude of this increase may be considerable, as in the case of sample H 25, Table 8, where the proportional limit has been raised from 15 000 lbs./in.^{2} to a little more than 56 000 lbs./in.^{2}, equivalent to 375 per cent. Such deformation does not, however, appear to modify the values of tensile strength, total elongation, or reduction of area when the specimen is finally broken. These results appear consistent with Bauschinger's deductions and the work of others mentioned, for a very rapid recovery from elastic overstrain and almost immediate elevation of the proportional limit would be expected at the temperature at which the stresses were applied.

Heating to a temperature above Ac_1 and thereafter cooling steel which has been overstrained at blue heat, 295° C (565° F), immediately restores the apparent elasticity of the metal at room temperature. Such thermal treatment does not lower the limit

of proportionality which in test at room temperature remains at a value approximating the previous overload at blueness.

Metal which is imperfectly elastic at room temperature because of previous overstrain at blue heat, 295° C (565° F), regains its elasticity after rest at room temperature. Steel subjected to overstrain at 465° C (870° F) behaves similarly, in so far as an increase above its original limit of proportionality is concerned. It is not quite clear from the several tests made if the immediate effect is to destroy the elastic properties, but such is probably the case.

Rosenhain (45) reported in some cases at least the hardening of steel by plastic strain was unidirectional, and that a piece of steel which had attained an apparently raised proportional limit as a result of tensile overstrain was really not hardened in every way, for, if tested in compression, it was found that for stresses of that kind the apparent proportional limit had been lowered, so that the total range of elasticity from the limit of compression to that in tension had not been materially altered.

In the search for differences in deformational characteristics with rise in temperature samples of marine boiler plate were subjected to stretching at several temperatures beyond the limit of proportionality and then tested in compression. The effect of such tensional overstrain at room temperature, blue heat and about 465° C (870° F) is a lowering of the limit of proportionality in compression at room temperature. When the steel is allowed to rest, the samples stretched at blue heat or below show a gradual decrease with time of the compressive limit of proportionality which, when taken in conjunction with the rise in this factor in tension, indicates that the range of elasticity is not altered but merely shifted. Steel similarly stretched at 465° C (870° F) behaves differently, however, for with increase in time of rest the compressive limit of proportionality rises until it approximates its original value, which in the cases shown in Figure 22 is reached after 71 hours. No interpretation of this latter effect can be attempted pending investigation of the effect of the magnitude of the tensional overstrain. There are, of course, many other questions which arise in connection with this subject which, as indicated heretofore, lead into a wide field for research but are not considered within the scope of this investigation.

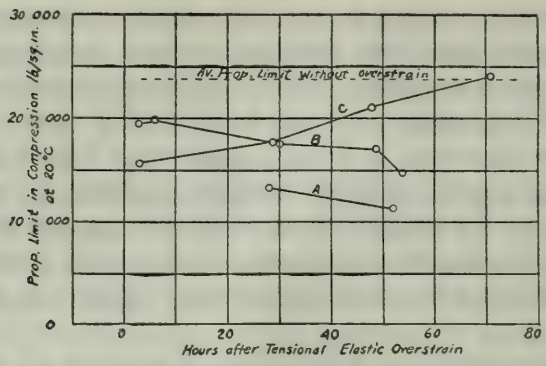

FIG. 22.—*Effect of time at room temperature on compressive proportional limit of marine boiler plate previously subjected to tensional elastic overstrain at various temperatures*

	Stressed in tension	
	Lb./in.²	At °C
A	45 000	20
B	45 000	295
C	30 000	563

Size of compression samples: ¾ inch diameter, 1½ inches long. Gage length of 1 inch used.

IV. EFFECT OF RATE OF LOADING ON THE TENSILE PROPERTIES OF STEEL AT VARIOUS TEMPERATURES

Whether or not steel is susceptible to variations in rate of loading in those ranges of temperatures including superheater and boiler operation, crude oil distillation, nitrogen fixation, etc., is of decided interest both from practical and theoretical standpoints, especially as there are comparatively little definite data available in the literature.

H. H. Campbell (47) reported the tensile properties of structural steel obtained under pulling speeds of 0.07 to 4.5 inches per minute. Both the yield point and tensile strength were shown to increase with rate of loading while the elongation and reduction of area remained practically constant. The fact that the last two factors which are independent of the accuracy of beam balance were not variable gives ground for thought concerning the causes for the susceptibility of strength and yield point to speed changes. When high pulling speeds are used, it becomes increasingly difficult for the operator properly to balance the beam of the testing machine, and the tendency toward "overbalancing" often results in high values.

A committee of the American Society for Testing Materials (46) has shown that the tensile properties of steels at room tempera-

ture are independent of the rate of extension, at least within limits of commercial practice or covered by speeds of from 1 to 6 inches per minute.

Little exact information is available relative to effects of rate variations in application of stress at elevated temperatures. Hopkinson and Rogers (18) reported that as the temperature rose the stress-strain relations in steel underwent remarkable changes, which might best be expressed by saying that the variously called "time effect," or "elastische nachwirkung," or "creeping," increased greatly with temperature. While such effects might be detected at ordinary temperatures, they attained a different order of magnitude at red heat (600° C).

The effect of "creeping" was found to make the determination of Young's Modulus a matter of some uncertainty, for the extension of a bar stressed at 600° C varied 15 per cent or more, depending upon the time of application of the load. For very short applications of the order of one or two seconds the strain produced approached a definite limiting value which, if used in determination of the modulus, made it independent of the manner of loading and a physical constant.

J. E. Howard (8) reported that the "rate of speed of testing which might modify the results somewhat with ductile material at atmospheric temperature had a very decided influence upon the apparent tenacity at high temperature." Steel containing 0.81 per cent carbon was tested at the adopted speed of the series (5 to 10 minutes for rupture) and also under rapidly applied stresses (in which case the time employed to reach the maximum stress was from 2 to 8 seconds). Nearly the same strength was displayed whether slowly or rapidly fractured at temperatures below about 315° C (600° F), this being a comparatively brittle metal at moderate temperatures. Above this temperature the apparent strength of the rapidly fractured specimens largely exceeded the strength of the others. The higher the temperature the wider apart in general were the results. An extreme illustration of this kind was furnished by a specimen tested at 766° C (1412° F) which when ruptured in two seconds showed a tensile strength of 62 000 lbs./in.^{2} as nearly as could be weighed, whereas at ordinary speed of testing a corresponding bar fractured at 33 240 lbs./in.^{2}.

Howard considered that the forces of cohesion tending to prevent rupture in a plane normal or oblique to the direction of the straining force and intermolecular friction developed during the

flow of the metal were prominent or controlling elements in the explanation of the behavior of steel under the conditions outlined.

More recently Rosenhain and Humfrey (29) have investigated the strength and fracture of soft steel at temperatures between 600 and 1100° C (1100 and 2000° F). They found mechanical discontinuity in the thermal critical range and an increased tenacity with rising rates of extension in testing small samples in vacuum.

In this investigation both increase in rates of extension over that adopted as standard (about 0.05 inch per minute average extension) and slow loading throughout the elastic range were studied and will be considered in order.

1. RAPID LOADING

(*a*) APPARATUS USED—The ordinary method of determining the limit of proportionality at room temperature by measurement of deformation under successive increases in load, which has also been used in this investigation at higher temperatures, probably requires the simplest form of apparatus but is not sufficiently flexible to allow much variation in rate of extension without materially affecting the accuracy of the results obtained, as obviously it is more than difficult to read several continuously moving indicators simultaneously even with a number of observers. The original apparatus for determination of the proportional limit as described in the first part of this report was therefore modified in some essential details, so that instruments indicating stress and strain could together be rapidly and repeatedly photographed by a motion-picture camera. The dials fastened to the frames shown in Figure 5 were turned so that their faces and a large load-indicating disk (Fig. 23) were practically in one plane. This latter was fastened to the uprights of the testing machine and by a system of pulleys connected to the screw operating the rider on the beam. One revolution of the disk, which was calibrated at 50-pound intervals, is equivalent to 42 500-pound load. Heavy white twine treated with resin was used to operate the various pulleys and served very well without noticeable slippage. The purpose of the auxiliary load indicator is to bring the instruments measuring applied stress and resulting strain together in a small field in order that they may be simultaneously photographed and as large an image as possible obtained on the motion-picture film.

For measuring deformation two geared dials with smallest direct reading of 0.001 inch were tried, as they were the only

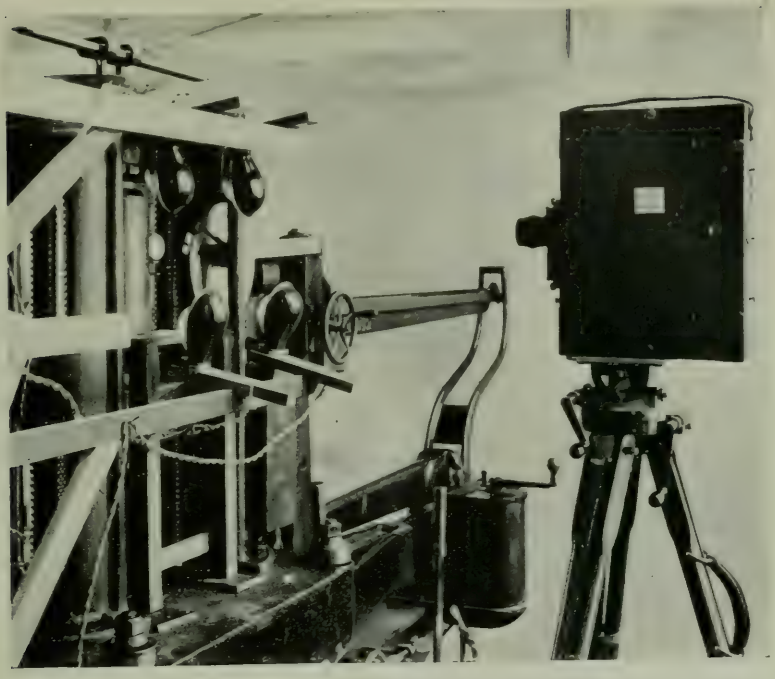

FIG. 23.—*Special apparatus used in determining tensile properties of steels at various temperatures under different rates of extension. (Auxiliary load indicator and motion-picture camera used in determining proportional limit)*

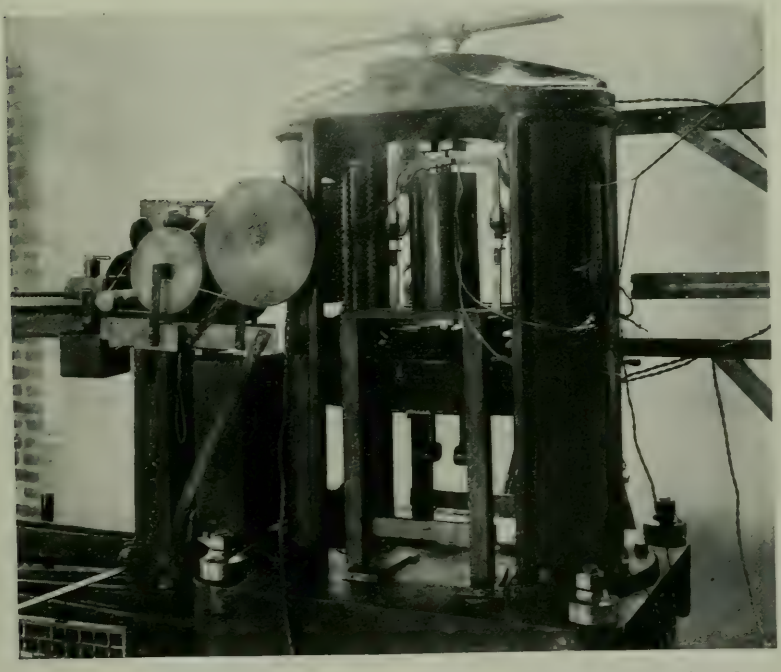

FIG. 24.—*Special apparatus used in determining tensile properties of steels at various temperatures under different rates of extension. (Shows method used in operating auxiliary load indicator)*

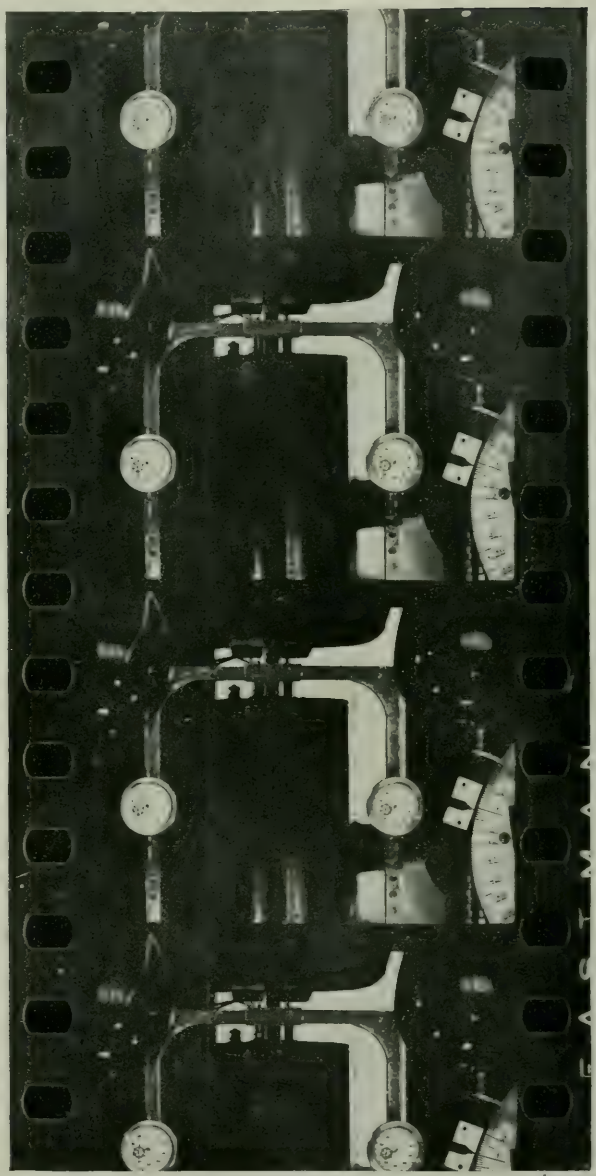

FIG. 25.—*Enlargement of portion of film obtained with apparatus shown in figures 23 and 24*

type available but, owing to the relatively small distortion obtained at room and slightly elevated temperatures with moderate load increments, it was not possible to obtain the desired accuracy in strain measurements without reading the dials, in projecting the film, to one-tenth of the smallest division. These were therefore discarded in favor of dials reading directly to 0.0001 inch, but these latter instruments proved erratic at times, and it is felt that they were responsible for the greater part of the rejected runs where it was impossible to obtain any stress-strain diagrams from the dial movements. This difficulty can be overcome, however, by the use of a special camera or lenses widening the field, so that dials with smallest direct reading of 0.001 inch, and estimated ten-thousandths can be used and read with ease from larger images on the films or preferably by the use of indicators free from gears.

The frames carrying the dials were firmly attached to the specimen at the 2-inch gage marks by means of two yokes, and the bar was then placed in the testing machine, heated to the desired temperature, and thermal equilibrium established before loading began. The complete assembly of this apparatus, which is shown in Figures 23 and 24, was carried out in the same manner as described in Section II, 2.

Load was next applied at any predetermined rate, and while the beam was at all times kept as nearly in balance as possible by the operator photographs were taken of the three constantly moving dials at the rate of about one a second. The loading was continuous until the bar was broken and no changes in gears or motor speed were made throughout the test. After development the film was projected on a screen where images of the dials were enlarged and as much time as was desired might be taken in obtaining individual readings. A simple projection device was used, and with this equipment it was found most convenient to obtain readings at a magnification of four times the original size. Under the conditions outlined above more photographs were obtained than required, but these served as a check on the accuracy of beam balance, which if not closely maintained resulted in serious deflections readily detected in the resulting stress-strain diagrams which were plotted in the usual manner. A portion of a typical film obtained in the determination of proportional limit by this method is shown enlarged in Figure 25, while a summary of results of tests made at various temperatures under different rates of extension is given in Figures 26 and 27.

Temperature, °C	Room	Room	Room	156	156	156	295	295	463	463	463
Extension, inch/min	0.5	0.8	1.6	0.5	0.8	1.6	0.5	1.6	0.5	0.8	1.6
No.	W-11	L-3	K-19	K-8	L-16	L-5	K-11	L-24	K-10	L-15	L-21

FIG. 26.—*Stress-strain diagrams obtained under different rates of extension at various temperatures*

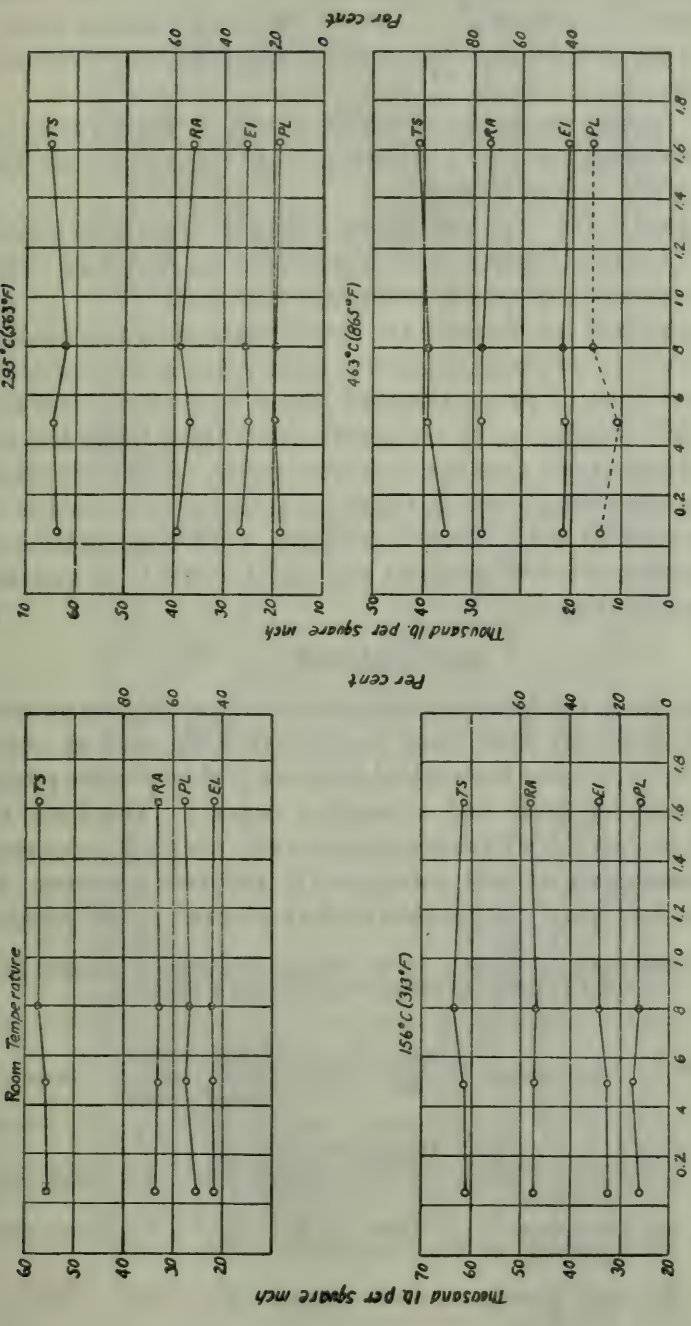

FIG. 27.—*Effect of rate of loading on the tensile properties of firebox boiler plate at various temperatures*

(*b*) EXPERIMENTAL RESULTS.—Based on tests made at room temperature, about 155° C (315° F), in the blue-heat range, 295° C (565° F), and at 465° C (870° F) under varying rates of extension up to 1.6 inches per minute, the following conclusions may be drawn:

1. The tensile properties of fire-box steel at temperatures up to and including the blue-heat range, 295° C (565° F), are independent of the rate of loading.

2. At 465° C (870° F) the tensile strength appears to increase slowly with rate of loading, while ductility as measured by elongation and reduction of area is practically constant.

At this highest temperature the stress-strain diagrams obtained were not, on the whole, satisfactory, largely due in all probability to the low limit of proportionality which is reached soon after the "slack" is taken up in the geared dials, these being the only type available at the time the tests were made. The proportional limit rate of loading curve in Figure 27 is therefore tentative and shown as a dotted line. There is, however, a difference in behavior of the metal at or below blue heat and 465° C (870° F) as indicated by strength variations.

2. SLOW LOADING

In addition to the foregoing tests samples were broken at about 155° C (315° F), at blue heat, 295° C (565° F), and at 465° C (870° F) by increasing the applied stress very slowly while passing the proportional limit and somewhat beyond. The load was increased 100 pounds at five-minute intervals over a definite range at each temperature, and subsequently the test specimen was broken at slow speed comparable to that adopted as the standard

TABLE 9.—Effect of Slow Loading on the Tensile Properties of Fire-Box Boiler Plate at Different Temperatures (Series 1 Steel)

Temperature of test		Rate of loading	Proportional limit	Tensile strength	Percentage elongation in 2 inches	Percentage reduction of area	Remarks
° C	° F		Lbs./in.²	Lbs./in.²			
156	313	Adopted standard [1]	26 600	58 100	24.9	49.3	Average 3 tests
156	313	6⅔ hours from 22 000 to 47 000 lbs./in.²	.....	64 350	22.8	45.9	Average 2 tests
295	563	Adopted standard [1]	14 330	66 430	25.9	53.1	Average 3 tests
295	563	3½ hours from 9000 to 20 000 lbs./in.²	.....	60 000	36.0	59.2	
463	865	Adopted standard [1]	13 200	47 460	33.6	68.5	Do.
463	865	6 hours from 9000 to 30 000 lbs./in.²	.....	33 600	42.0	78.4	

[1] Adopted standard averages about 0.05 inch per minute extension.

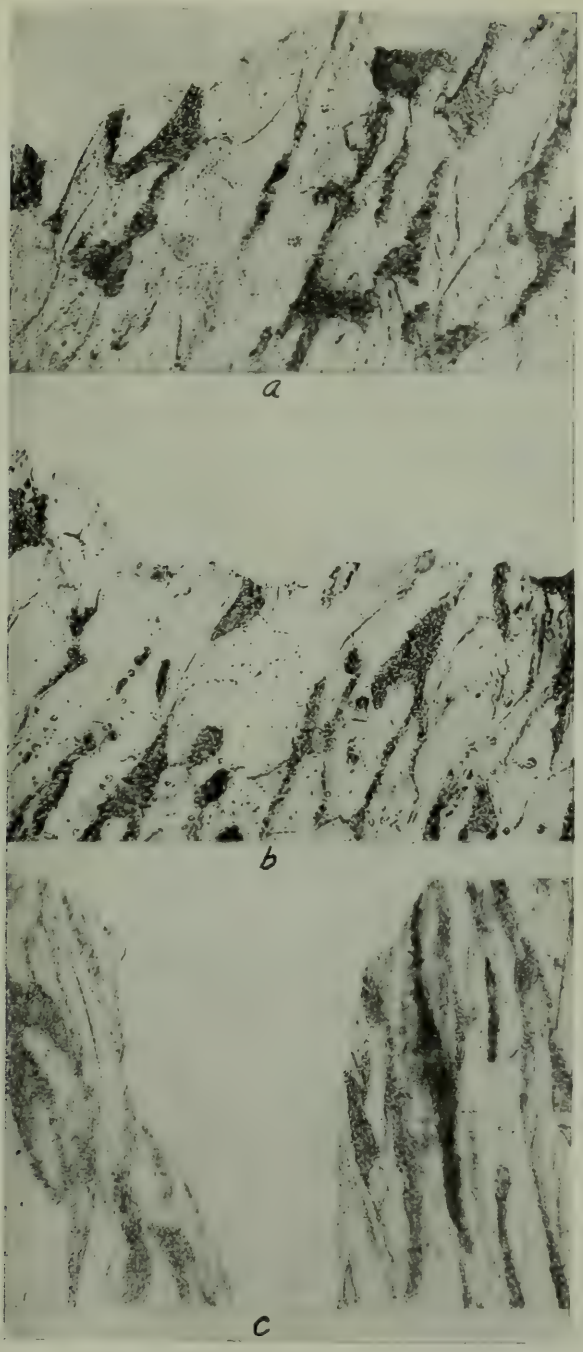

FIG. 28.—*Microphotographs of the fractures of hot-rolled fire box boiler plate at various temperatures.* × 500

a, Specimen A8; broken in tension at room temperature. *b*, Specimen A22; broken in tension at blue-heat (295° C). *c*, Specimen A5; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

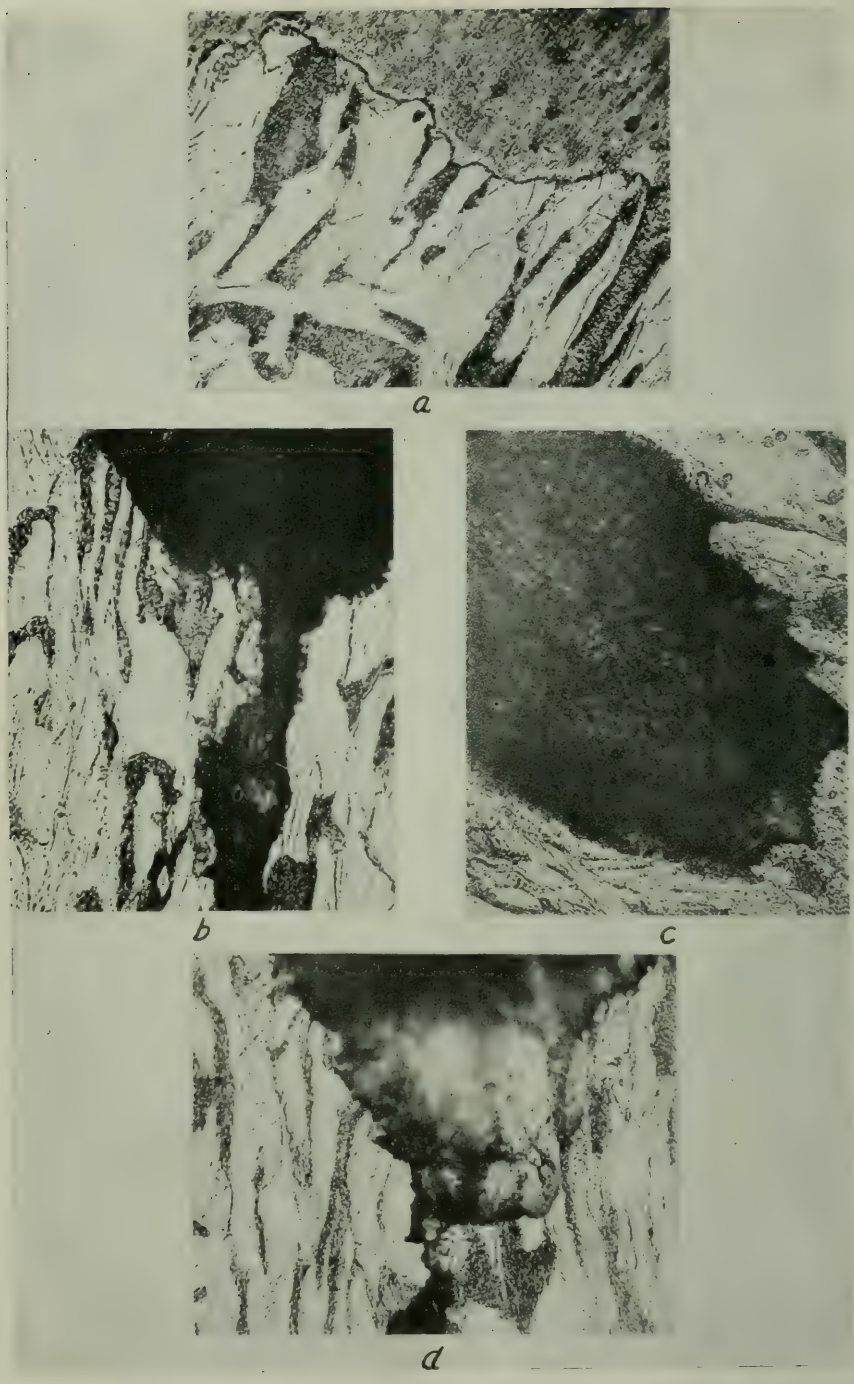

FIG. 29.—*Microphotographs of the fractures of cold-rolled marine boiler plate at various temperatures.* × 500

a, Specimen F1; broken in tension at room temperature. *b*, Specimen F9–A; broken in tension at blue-heat (295° C). *c*, Specimen F9–B; broken in tension at blue-heat (295° C). *d*, Specimen F14; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

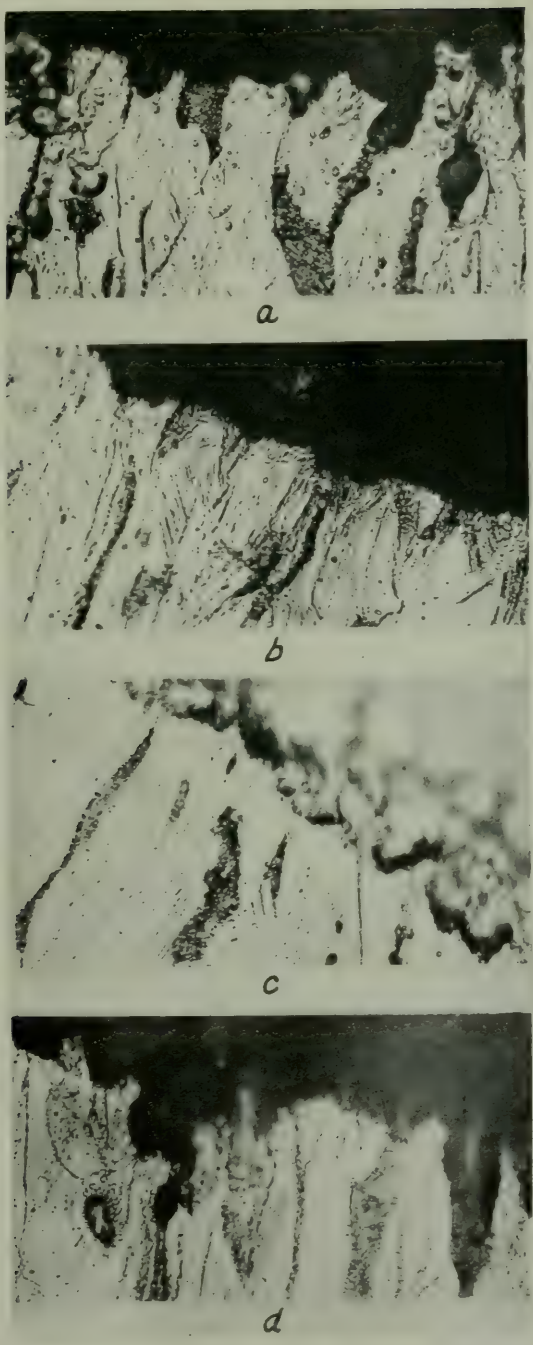

FIG. 30.—*Microphotographs of the fractures of blue-rolled fire box boiler plate at various temperatures.* × 500

a, Specimen X7–1A; broken in tension at room temperature. *b*, Specimen X7–1B; broken in tension at room temperature. *c*, Specimen X7–4; broken in tension at blue-heat (295° C). *d*, Specimen X7–7; broken in tension at 465° C. Etched with 2 per cent nitric acid in alcohol

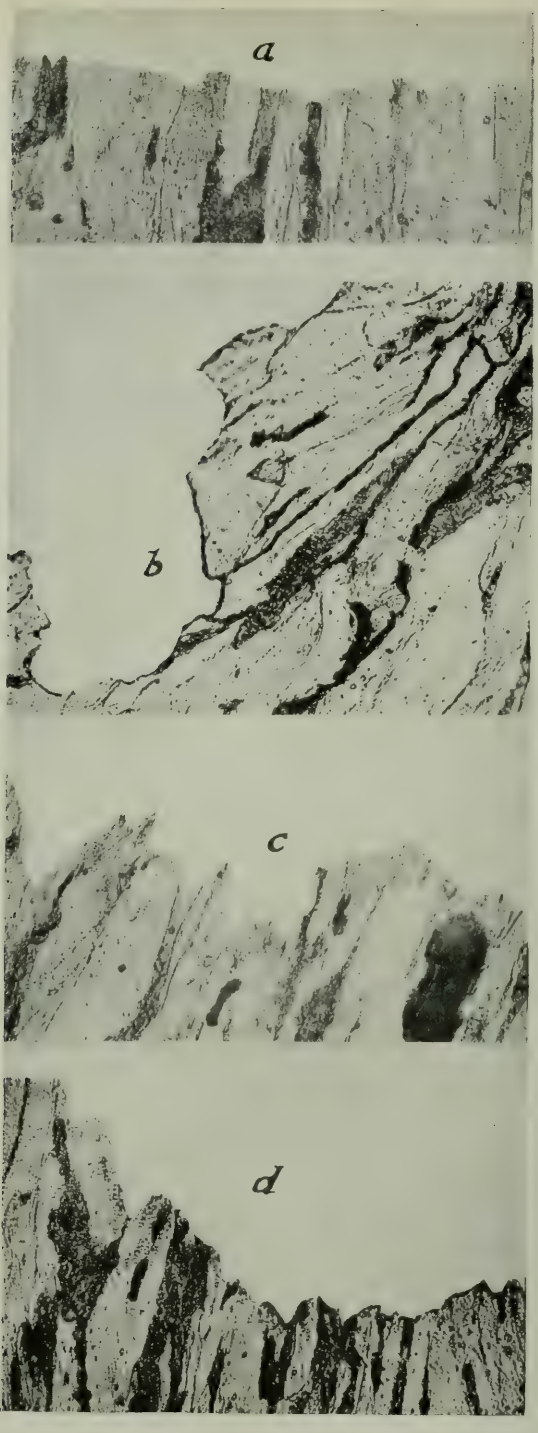

FIG. 31.—*Microphotographs of the fractures of fire box boiler plate obtained at 465° C. under different rates of loading.* × 500

a, Specimen K_{24}; broken under standard rate of loading adopted. (About 0.05 inch per minute free pulling speed of head of testing machine.) *b*, Specimen K7-A; broken at 0.5 inch per minute. (Free travel of head of testing machine.) *c*, Specimen K7-B; broken at 0.5 inch per minute. (Free travel of head of testing machine.) *d*, Specimen L_{20} broken at 1.6 inch per minute. (Free travel of head of testing machine.) Etched with 2 per cent nitric acid in alcohol

throughout the investigation. Such slow loading raises the strength and decreases ductility at 155° C (315° F), but the steel exhibits decreased strength and higher ductility when so tested at blue heat, 295° C (565° F), or above than when broken in the ordinary manner (Table 9).

V. MICROSCOPIC EXAMINATION

Fractures of steel broken at various temperatures at different rates of loading and under varying conditions of mechanical work were examined under the microscope and were found to be generally transcrystalline. Minor differences appear under certain conditions, such as, for example, the apparent tendency for the fracture to follow more deeply along the grain boundaries and particularly at the junctions of ferrite and pearlite when the steel is broken under very slowly increasing stress. In general, no marked differences in behavior were observed, as will be evident from microphotographs shown in Figures 28 to 31, inclusive.

VI. DISCUSSION AND SUMMARY

1. AMORPHOUS METAL THEORY

Before concluding this report some of the observed phenomena will be briefly examined in the light of the amorphous theory of metals by which deformation is considered to take place along planes of easy slip in crystals. Along these gliding surfaces amorphous metal is formed which is likewise assumed to have temporary mobility and is followed by "setting" to produce extremely hard and rigid layers. This temporary mobility has been conveniently used in explaining the immediate loss of elasticity of overstrained metal and the subsequent elevation of the elastic limit with time.

At the melting point the cohesion of the amorphous phase is zero and that of the crystalline a finite value. As the temperature is lowered the cohesion of the former increases more rapidly than that of the latter until at some temperature (called the equicohesive temperature) the cohesion-temperature curve of the amorphous phase intersects that of the crystalline.

The difficulties of explaining certain observed phenomena and the basis for assuming a low-temperature allotrope in iron have recently been very completely stated by Jeffries (33) (34), but while such questions as why metals other than iron show no "blue-

heat" range can not be satisfactorily answered by the amorphous metal theory or by differences in cohesion alone, the former is probably the most widely used and the hypothesis most generally adhered to.

The differences in behavior of the limit of proportionality in compression with time in steel previously subjected to tensile overstrain above and at blue heat (respectively, 465 and 295° C) are not easily explained. The assumption of temporary mobility of the amorphous phase which has been used in explaining apparent loss of elasticity of iron overstrained at room temperature serves likewise for similar effects obtained at room temperature for steel subjected to overstrain at high temperatures. It is not clear why the unidirectionality of elastic recovery at room temperature, and in these tests found at blue heat, should be upset at the highest temperature, 465° C (870° F), though it is suggested that the lowered cohesion of the crystalline phase permits more nearly indiscriminate slip along crystallographic planes instead of those most nearly normal to the straining force, so that after setting of the amorphous phase and coincident recovery of elasticity hardening is produced in all directions instead of along certain ones as found at blue heat and temperatures below. Such indiscriminate slip might, of course, be favored under certain conditions of overstrain at blue heat and temperatures below, but, as previously indicated, insufficient data have been obtained to allow definite statements. That the hardening produced by blue and cold rolling is largely in the direction parallel to the axis of deformation is shown by the relatively small increases in strength obtained from such work on transverse samples.

It is also conceivable that block movement of masses of atoms may break up into movements of smaller blocks if sufficient time is allowed. In other words, when a definite load in excess of the limit of proportionality is applied to steel at about 465° C (870° F), deformation which at first takes place in block movement along planes of easy slip proceeds by further movement in these original blocks of smaller units resulting in creeping observed by Hopkinson and Rogers (18), Howard (8), and others. This crystalline fragmentation would result in a general weakening of the cross section as the amorphous metal formed is weakened by the high temperature. As such an effect requires time and relatively large deformation, the slower the loading the lower the strength expected.

At 155° C (315° F) the cohesion of the amorphous phase is considerably greater than that of the crystalline and, in slow loading, time may be given for the "setting" of the amorphous metal formed. Hardening is therefore produced and results in higher strength. At both ordinary and rapid rates of loading insufficient time is allowed for this setting and no marked changes in strength are observed.

At blue heat, 295° C (565° F), the cohesion of the amorphous phase is less than at 155° C (315° F) but greater than at 465° C (870° F), which makes the behavior of steel in this range apparently anomalous, for in the range of maximum strength slow loading results in a decrease in this factor.

While the amorphous metal theory is at this time the most widely used, it is not wholly adequate but is probably the best working hypothesis. Our knowledge of the fundamentals connected with changes in iron and steel below the thermal critical ranges will probably not be greatly enhanced by further determinations of the mechanical properties alone. Such other methods as used by the Braggs [8] and others, while perhaps offering serious experimental difficulties, will without doubt more quickly lead to more truthful conceptions and explanations of observed phenomena.

2. SUMMARY

1. An apparatus has been devised for studying the changes in tensile properties of metals at various temperatures, including determination of the limit of proportionality. A modified form of this equipment has been devised for studying the effects of variation in rapid rates of stress application on these properties, and this has been described.

2. The proportional limit of low-carbon steel determined on longitudinal specimens does not decrease directly with first rise in temperature above that of the room, as has been so often reported, but is either maintained at about its room temperature value throughout a definite temperature range or increases before a marked drop in its value is observed.

3. Changes in tensile strength and ductility of several grades of boiler plate from about 20 to about 465° C (70 to 870° F) have been determined. The general inflections in curves representing variations in these factors with rise in temperature are the same for longitudinal and tranvserse specimens, and show maximum

[8] W. H. Bragg and W. L. Bragg, X rays and crystal structure.

strength between 250 and 300° C (480 to 570° F). Maximum ductility occurs in longitudinal tests at 200 to 300° C (390 to 570° F) and in transverse throughout a wider range from 150 to 300° C (300 to 570° F). Above blue heat, 295° C (565° F), there is a marked drop in strength which is accompanied by decided inflections in curves showing elongations and reductions of area, indicative of a change in the character of the metal.

4. The effect of moderate cold-rolling, which raises the elastic properties and to some extent the tensile strength and likewise lowers ductility at room temperature, is, in general, maintained throughout the range 20 to 465° C (70 to 870° F). However, at blue heat the increase in limit of proportionality due to previous cold work is greatly in excess of that observed at room temperature and is accompanied by an increased ratio, cold to hot rolled elongation.

5. If cold-rolled steel is heated for a short time at this temperature (blue heat) and cooled, there results a decided elevation in the limit of proportionality with no material change in tensile strength or lowering of the ductility. This is of practical interest in production of such material as cold-drawn light-wall tubing often manufactured under definite tensile requirements, where "bluing" subsequent to the last cold pass will result in improved tensile properties.

6. The fact that blue-rolling is more effective than the same amount of cold-rolling in raising the strength of low-carbon steel and in decreasing ductility at room temperature has been confirmed. Six and one-quarter per cent reduction in thickness at blue heat produces about the same increase in strength at temperatures up to and including 295° C (565° F) (blue heat) as twice this cold reduction. Above blue heat the strength of the cold rolled steel is slightly in excess of that blue-rolled, though the general shape of the tensile properties temperature curves for both conditions mentioned is the same.

7. Blue work (6.25 per cent reduction in plate thickness) is more effective in raising the limit of proportionality of low-carbon steel at temperatures below the blue-heat range than twice this work in the cold, but at blue heat the increase in this factor is very much greater in the cold-worked metal. At higher temperatures the increase produced by both methods of working is approximately the same.

8. In samples taken transversely the changes in tensile properties throughout the range 20 to 465° C (70 to 870° F) resulting

from cold and likewise blue rolling are small compared to those observed in longitudinal tests. The similarity in the observed changes in tensile properties of low-carbon steel brought about by blue and cold deformation indicates that the character of the effects produced are similar but effected more rapidly at blue heat. While longitudinal and transverse tensile tests do not wholly define the character of the metal, sufficient evidence is presented to show the extreme susceptibility of steel to deformation in the blue-heat range, and for that reason alone such working should be avoided. A marked decrease in ductility results both at room and elevated temperatures. There is, however, little or no evidence to prove that a limited amount of blue work permanently injures the metal, for, as pointed out by Howe (38) and here substantiated by the author, restoration of ductility may be obtained by annealing.

9. A few experiments relating to the effects of tensional elastic overstrain at various temperatures on the tensile properties of low-carbon steel at room temperature, blue heat, and 465° C (870° F) have been carried out.

10. A study of the effects of variations in rate of stress application from the adopted standard estimated at 0.05 inch average extension per minute to 1.6 inch per minute shows the tensile properties of steel to be independent of the rate of loading at temperatures up to and including blue heat. At 465° C (870° F) the tensile strength appears to increase slightly with increased rate of loading without noticeable change in ductility.

11. Slow loading in the range about the proportional limit results in increased strength and decreased ductility at 155° C (315° F) and decreased strength and increased elongation and reduction of area at blue heat 295° C (565° F), and above 465° C (870° F).

12. A brief discussion of the observed effects in the light of the amorphous metal theory has been given.

3. ACKNOWLEDGMENTS

The large number of tests reported in this investigation were made at intervals over a considerable period of time and required the aid of a number of assistants. Among these acknowledgments are due to the following: Donald S. Clements, temporarily laboratory assistant, Bureau of Standards, for aid in construction of the original apparatus and in making the first series of tests; A. L. Meyer, metallurgist, Lukens Steel Co., Coatesville, Pa.,

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TEST OF A HOLLOW TILE AND CONCRETE FLOOR SLAB REINFORCED IN TWO DIRECTIONS

BY

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TEST OF A HOLLOW TILE AND CONCRETE FLOOR SLAB REINFORCED IN TWO DIRECTIONS.

By W. A. Slater, Arthur Hagener, and G. P. Anthes.

ABSTRACT.

This paper describes the test of a large slab built of hollow clay tiles with reinforced concrete ribs between the rows of tiles and parallel to both panel sides. To avoid complication of results due to settlement of footings a foundation consisting of an inverted flat slab under the entire test structure was employed. Heavy loads were placed on the slabs and measurements of strains and deflections were taken in about 1,600 places at intervals during the loading. The load was left in place for over a year. The purpose of the test was to obtain empirical data to form a basis for the design of such slabs.

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I. INTRODUCTION.

The purpose of the test herein reported was to obtain data which would afford a basis for the design of a concrete and hollow tile floor reinforced in two directions. The test was planned to obtain information on: (1) The effect of variation in the ratio of length to width of panels upon the bending moments in two directions at right angles to each other, (2) the relation of maximum negative moment to maximum positive moment in a given panel, (3) distribution of tensile and compressive stresses at sections of maximum negative and maximum positive moment, (4) the amount of deflection of the slab and girders under different loadings, (5) the length of reinforcement required to give proper anchorage beyond points of support, and (6) the extent to which the tiles share in resisting the compressive stresses and the shearing stresses in the slab.

For the purpose of obtaining the data desired, a large floor slab, consisting of 18 panels, was constructed at Waynesburg, Ohio, in 1919. Approximately 900 gauge lines for measurement of deformations were established in the reinforcement, 500 gauge lines in the concrete, and 75 gauge lines in the tiles of the slab. Deflections were observed in 40 places.

The test was made for J. J. Whitacre, of Waynesburg, Ohio, under the direction of Mr. Slater, representing the Bureau of Stand-

ards, with the cooperation of Prof. R. H. Danforth, of the Case School of Applied Science, Cleveland, Ohio. The slab was constructed under the supervision of Mr. Anthes. The tiles used were furnished by the Whitacre Fireproofing Co. of Waynesburg, Ohio. The observations used in the report were made by Messrs. Anthes, Hagener, and G. G. Scofield, all experienced observers in this kind of investigation. R. R. Zipprodt, of the bureau, assisted during the concreting of the slab and its preparation for test and in organizing the work of testing.

II. MATERIALS, CONSTRUCTION, AND TESTING.

1. MATERIALS.

Tests of the materials used in the slab were made in the laboratory of the Case School of Applied Science, Cleveland, Ohio, under the direction of Prof. R. H. Danforth.

(*a*) REINFORCEMENT.—Six specimens of the reinforcement used in the slab and three specimens of the reinforcement used in

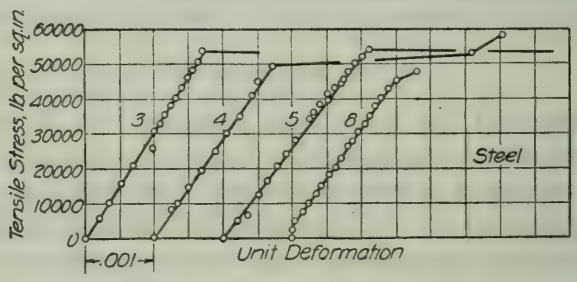

FIG. 1.—*Stress-deformation curves for control specimens of reinforcing steel.*

the girders were tested. The results of these physical tests are given in Table 1. The stress-deformation curves for the reinforcement are given in Figure 1.

(*b*) CONCRETE.—The aggregate which consisted of sand and gravel taken from a near-by stream contained a considerable amount of soft material.

Tests were made at the Structural Materials Research Laboratory, Lewis Institute, Chicago, on concrete containing 1 part of Portland cement made up of a mixture of five brands purchased in Chicago, 2 parts of this sand, and 4 parts of the gravel from which the material passing a No. 4 sieve had been rejected. The sand was graded from dust to about one-fourth inch and the gravel up to about 1 inch. The average strength of four 4 by 8 inch cylinders tested at 7 days was 890 lbs./in.^{2}, and that of two cylinders tested at 28 days was 1,630 lbs./in.^{2}.

TABLE 1.—Tests of Slab and Girder Reinforcement.

REINFORCEMENT USED IN SLAB.

Reference number.	Diameter of bar.	Yield point.	Ultimate strength.	Modulus of elasticity.
	Inch.	Lbs./in.²	Lbs./in.²	Lbs./in.²
1	0.50	54,280	86,490	.....
2	.50	53,880	86,680	.....
3	.50	52,710	88,690	32,100,000
4	.50	52,890	86,240	28,500,000
5	.50	54,400	88,400	27,800,000
6	.50	53,200	86,850	.....
Average	.....	53,560	87,220	29,500,000

REINFORCEMENT USED IN THE GIRDERS.

7	0.875	49,100	74,800	.....
8	1.00	45,800	78,800	29,350,000
9	1.125	44,100	74,500	.....
Average	.....	46,300	76,000	29,350,000

TABLE 2.—Compression Tests of Concrete.

Reference number.	Date poured (1919).	Age at test.	Compressive strength.	Modulus of elasticity.[1]	Age at test.	Compressive strength.
		Days.	Lbs./in.²	Lbs./in.²	Days.	Lbs./in.²
10	Oct. 2	.....	.....	.....	118	2,690
11	do	.....	.....	.....	118	3,520
12	do	.....	.....	.....	118	3,100
13	Oct. 6	37	2,940	2,275,000	.....	.....
14	do	42	2,370	.....	.....	.....
15	do	42	2,740	.....	.....	.....
16	do	.....	.....	.....	114	2,460
17	Oct. 7	28	1,680	.....	.....	.....
18	do	.....	.....	.....	113	2,960
19	do	38	2,130	.....	.....	.....
20	do	28	1,470	.....	.....	.....
21	do	38	1,330	.....	.....	.....
22	do	38	1,760	.....	.....	.....
23	do	38	2,160	.....	.....	.....
24	Oct. 8	.....	.....	.....	112	3,370
25	do	.....	.....	.....	112	3,190
26	do	.....	.....	.....	112	2,480
27	do	27	1,590	2,700,000	.....	.....
28	do	27	2,220	2,020,000	.....	.....
Average	.....	35	2,030	2,330,000	115	2,980

[1] The initial modulus of elasticity is given.

TABLE 3.—Strength and Initial Modulus of Elasticity of 6 by 12 by 12 inch Clay Tiles.

Reference number.	Load applied on open end of tile.		Reference number.	Load applied perpendicular to axis of cells on 6 by 12 inch face.	
	Compressive strength.[1]	Modulus of elasticity.		Compressive strength.[1]	Modulus of elasticity.
	Lbs./in.²	Lbs./in.²		Lbs./in.²	Lbs./in.²
29	3,425	5,500,000	37	3,290	.....
30	4,850	.....	38	3,580	2,360,000
31	5,500	4,900,000	39	4,700	.....
32	4,570	.....	40	4,660	4,800,000
33	5,040	5,300,000	41	3,050	.....
34	5,080	.....	42	4,820	6,100,000
35	5,040	.....	.....	.....	.....
36	5,880	5,100,000	.....	.....	.....
Average	4,920	5,200,000	.....	4,010	4,420,000

[1] The compressive strength is the total load divided by the area of the tile walls cut by a section through the cells parallel to the bearing surfaces.

The concrete used in constructing the slab contained 1 part cement and 5 parts of the mixed aggregate. The concrete used near the centers of spans of the girders contained a small percentage of aggregate as large as 2 or 3 inches in greatest diameter. For the concrete used in the slab the aggregate coarser than 1 inch was screened out.

All the concrete was mixed in a drum mixer which was set up near the northeast corner of the slab. The concrete was transported in wheelbarrows to the place where it was to be used. Placing of the concrete began on October 2, 1919, and was completed on October 9. The length of time consumed by the actual work of placing the concrete was about four and one-half days. R. R. Zipprodt, representing the bureau, was present during all the work of placing the concrete. Control cylinders (6 by 12 in.) of

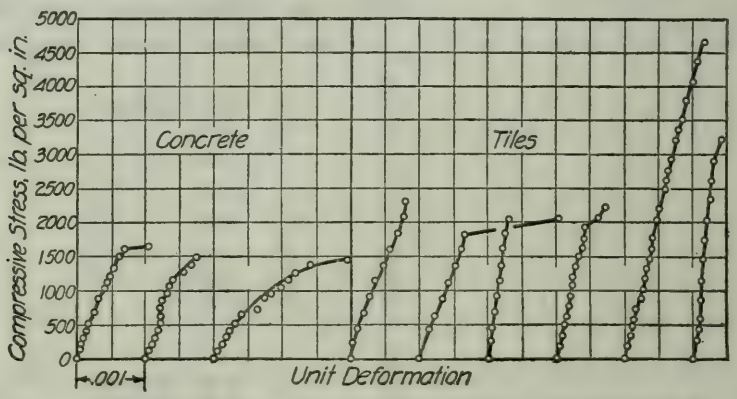

FIG. 2.—*Stress-deformation curves for control specimens of concrete and tiles.*

the concrete were taken from such parts of the work as would make them representative of the concrete in the structure, and were subsequently tested in compression. Stress-deformation curves for the concrete cylinders are given in Figure 2. The strength and modulus of elasticity are given in Table 2.

(*c*) TILES.—The tiles were of the six-cell type, 6 by 12 by 12 inches in size, and weighed approximately 30 pounds each. Test results for the tiles are given in Table 3. The stress-deformation curves for the tiles are given in Figure 2.

2. DESIGN AND CONSTRUCTION OF SLAB.

The test slab had less reinforcement than would be required by most existing standards for the design of floors for even the smallest live loads specified in building codes. Certain tests which had already been made on slabs of similar construction in-

dicated strengths great enough to point to the desirability of using very light reinforcement in the test slab. The general features of the design were: (1) Continuity of all portions of the structure; (2) a span as large as possible considering the expense of construction and of testing; (3) panels of three different ratios of length to width, 1, 1.2, and 1.4; (4) slab thickness equal to one thirty-second of the short span center to center of supports; (5) reinforcement which was very small in amount (0.26 per cent) and which was the same for positive as for negative moment; and (6) girders heavy enough to carry a maximum load considerably greater than that which a rational analysis indicates that the slabs would carry.

An analysis of the structure indicates that on the basis of the recommendations of the final (1916) report of the Joint Committee on Concrete and Reinforced Concrete[1] the interior panels of the slab would be suitable for total live and dead working loads of about 83, 67, and 48 lbs./ft.^{2} for the square, intermediate, and long panels, in the order given.[2] Taking the weight of the slab at 50 lbs./ft.^{2}, it will be seen that under these recommendations the design live loads would be 33, 17, and minus 2 lbs./ft.^{2}, respectively. More exact analysis by rational methods[3] would give design loads not greatly different from those stated here.

This general statement has been made in order to give a basis for comparing the loads carried by the slab with those to be expected on the basis of ordinary standards for design.

The slab was 117 feet 6 inches long by 50 feet wide and was divided into 18 panels. Six of these panels were 16 feet square, six were 16 feet by 19 feet 3 inches, and six were 16 feet by 22 feet 6 inches. These panel dimensions were measured from center to center of supporting columns. The panels were supported by reinforced concrete girders, the stems of which were generally 12 inches wide, making the clear spans about 12 inches less than the dimensions given above. The slab was made of 6 by 12 by 12 inch clay tiles arranged in rows at right angles to each other and separated in both directions by ribs of concrete

[1] Transactions A. S. C. E., 81, p. 1101; 1917.

[2] As recommended by the joint committee report the negative moment was taken as $\left(\frac{l}{b}-0.5\right)\frac{wb^2}{12}$ in the direction of the short span and $\left(1.5-\frac{l}{b}\right)\frac{wl^2}{12}$ in the direction of the long span, and the positive moment was taken the same as the negative moment. Here w is the uniform load per unit of area. l is the long span, and b is the short span. The values of l and b were taken as the clear spans between edges of girders.

[3] Westergaard and Slater, "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, Figs. 7 and 8, p. 435 and 436, respectively; 1921.

4 inches wide and 6 inches deep. The tiles throughout the slab were laid with the cells running in the north-and-south direction. The ends of the tiles were left open allowing a small amount of concrete (from 15 to 20 per cent of the volume of the cells) to enter, making the tiles form an integral part of the slab. The outer walls of the tiles were $\frac{3}{4}$ inch thick and the partition walls were $\frac{5}{8}$ inch thick. The outer surface was scored with grooves

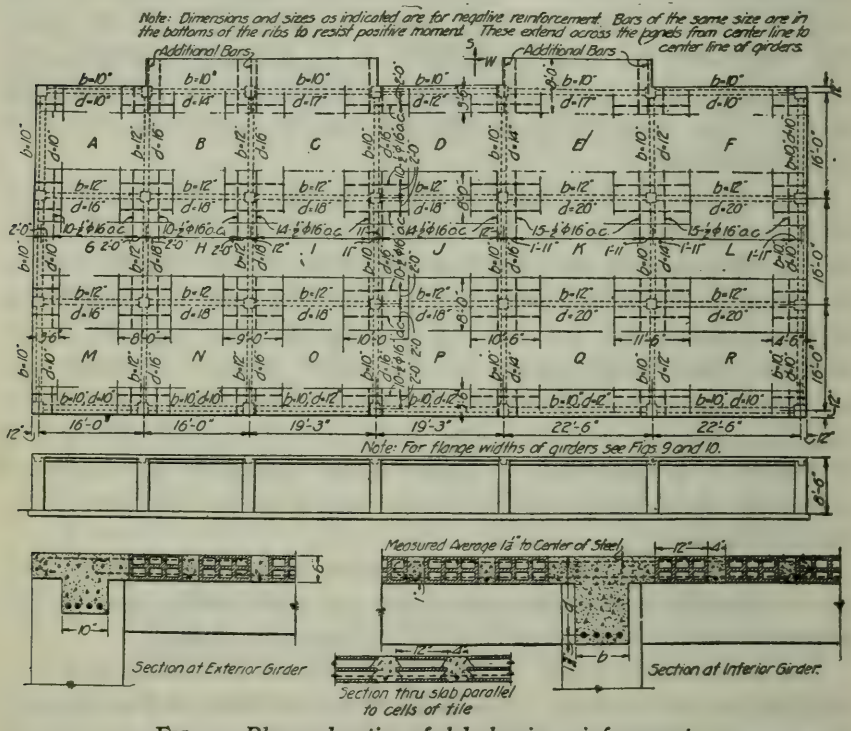

FIG. 3.—*Plan and section of slab showing reinforcement.*

$\frac{3}{16}$ inch deep and about $\frac{1}{2}$ inch wide extending in the direction of the cells.

Each concrete rib between rows of tiles was reinforced in the bottom with one $\frac{1}{2}$ inch plain round bar extending the full length of the rib, and in the top with one $\frac{1}{2}$ inch plain round bar at each end, which extended from a point one-fourth of the span length from the end of the rib through the top of the supporting girder one-fourth of the span length into the rib on the opposite side of the girder. The centers of the bottom bars were 1 inch and $1\frac{1}{2}$ inches from the bottom surface of the rib in the short and in the long spans, respectively. The centers of the top bars were $1\frac{1}{4}$ inches below the top of the ribs. The top bars were hooked at their ends to prevent slipping. Figure 3 shows the detail design

FIG. 4.—*Girder reinforcement in place.*

FIG. 5.—*Slab reinforcement in place.*

FIG. 6.—*Tiles in place ready for concreting.*

FIG. 7.—*General view of completed slab.*

FIG. 8.—*View of slab from below.*

of the slab, except that the areas of the tension reinforcement for the girders are shown in Figure 38 and the widths ofthe concrete flanges of the girders—that is, the distance from the center lines of the girders to the edge of the first row of tiles—are shown in Figures 9 and 10. Figures 4, 5, and 6 are views of the slab during construction. Figures 7 and 8 are views of the completed slab.

In order to avoid any chance of settlement of the footings, a continuous flat slab foundation was constructed. This foundation was 12 inches thick. The areas in the interior portions of the panels were of reinforced concrete and hollow tile construction. An area 9 feet by 9 feet 8 inches immediately surrounding each interior column was entirely of reinforced concrete.

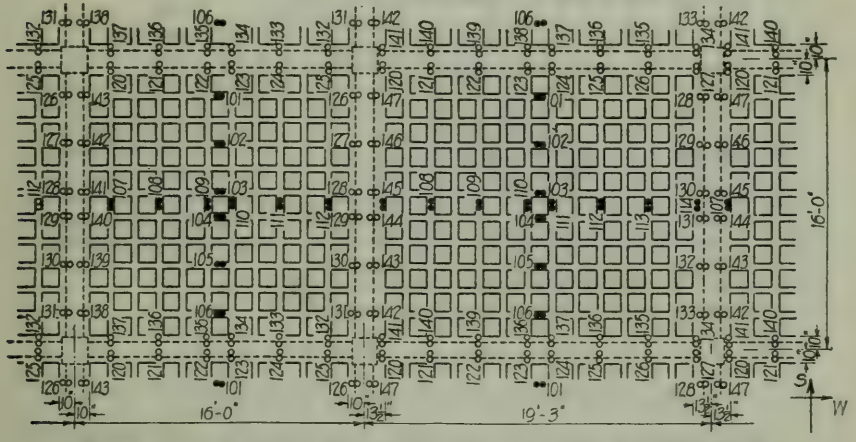

FIG. 9.—*Layout of gauge lines for typical square and intermediate panels.*

Work on the footings began July 26, 1919. The footings were poured between August 23 and September 2. The columns were poured on September 25 up to the soffits of the girders. The slab was poured between October 2 and 10, 1919.

3. TESTING.

(*a*) OBSERVATIONS.—Figures 9 and 10 give the layout of the gauge lines on the reinforcement and concrete of the slab for positions of positive moment and for positions of negative moment for a typical panel of each of the three sizes. In addition to the gauge lines indicated in Figures 9 and 10, gauge lines were also established in the reinforcement in the tops of the girders at the edges of the columns and in the reinforcement in the bottoms of the girders at the centers of the spans. Gauge lines were also

placed at intervals on certain bars in the tops of the ribs in order to locate the points of zero stress and also in some of the tiles in the top and some in the bottom of the slab at points of maximum stress. For location of gauge lines to determine points of zero stress, see Figure 38. The deformations in the reinforcement and in the concrete under the applied loads were observed with a Berry strain gauge [4] having a gauge length of 4 inches and in the tiles with a strain gauge having a gauge length of 8 inches.

Deflection observations were made at the centers of the panels and at the centers of certain girders.

(*b*) Loading.—Radial chimney bricks of the type shown in Figure 14 were used as loading material. The bricks were of two

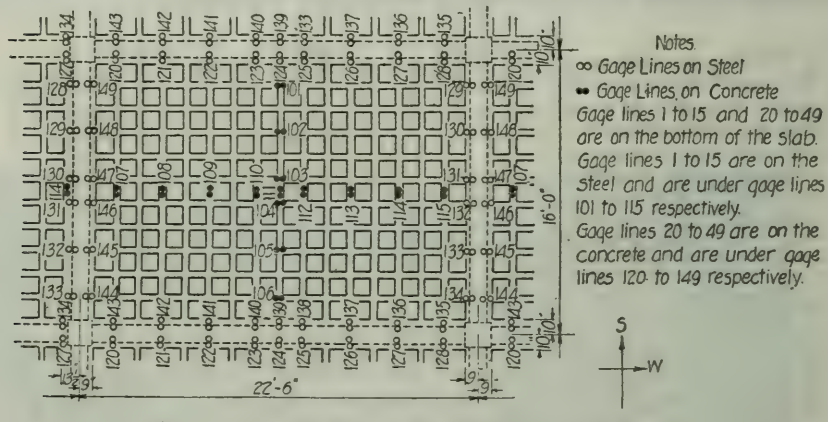

Fig. 10.—*Layout of gauge lines for typical long panel.*

sizes, weighing 12 and 10 pounds, respectively, per brick. To prevent arching of the load and to secure accessibility to all of the gauge lines on top of the slab, the load on each panel was divided into four stacks as shown in Figure 18. This left an aisle 18 inches wide over each girder and along the center line of each panel in the direction of each pair of sides of the panel.

In forming stacks bricks of like size were placed in a layer. The 12-pound bricks gave a load of approximately 25 lbs./ft.^{2} per layer on the square panels and 27.5 lbs./ft.^{2} per layer on the intermediate and long panels. The 10-pound bricks gave a load of approximately 23 lbs./ft.^{2} per layer on the square panels and 25 lbs./ft.^{2} per layer on the intermediate and long panels. The method of computing the load per square foot is stated in section II, 4.

[4] W. A. Slater and H. F. Moore, "Use of the strain gauge in the testing of materials," Proc. Amer. Soc. Test. Mat., 13, p. 1019; 1913. A. N. Talbot and W. A. Slater, "Tests of reinforced concrete buildings under load," Bulletin 64, Univ. of Illinois Engineering Experiment Station; 1913.

To avoid difficulty in stacking the bricks, due to slight irregularities in the surface of the slab, sand cushions 1½ inches thick were laid before any bricks were placed. The sand was retained in place by wooden frames which defined the sizes of the piles and the location of the aisles and served as screeds for leveling off the sand cushions.

The first series of loadings began on December 20, 1919, and continued at intervals up to February 5, 1920. The loaded areas and the intensities of the load on the latter date are given in Figure 18. This load is referred to throughout the paper as the "maxi-

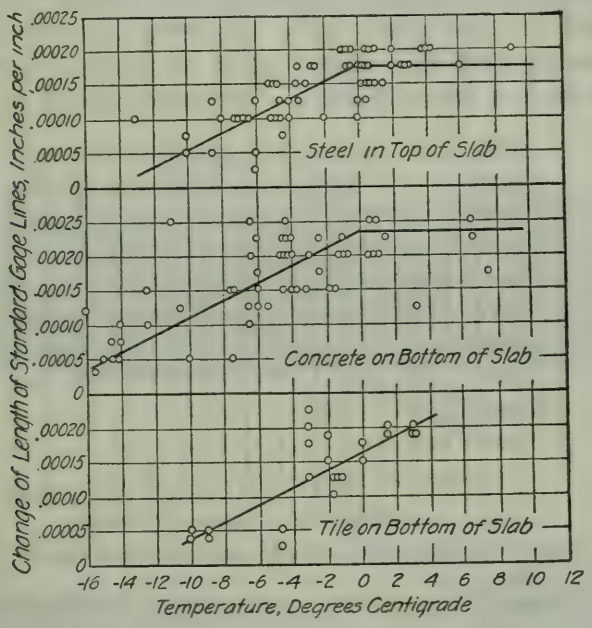

FIG. 11.—*Temperature-deformation curves for small unstressed slabs for January and February, 1920.*

mum uniform load." A view of the load is given in Figure 13. For this total amount of load no other practicable distribution would have produced a higher negative moment. The term uniform here applies to the distribution of the load over panels of the same size. The only exception to the uniformity of load for all panels of the same size was in the case of the corner square panels. (See Fig. 18.)

The maximum uniform load was left in place until April 3, 1920. Shifting of the load from one part of the slab to another was then begun and was continued up to April 22, 1920. The load was shifted with the purpose of maintaining as nearly as pos-

sible a constant stress in the reinforcement resisting the negative moments, and at the same time of increasing the stress in the reinforcement resisting positive moment in typical panels. The loaded areas and the intensities of the load on April 22, 1920, are given in Figure 19. Views of that load are given in Figures 14 and 15.

Table 4 gives a record of the loading from December 20, 1919, to April 22, 1920.

The load remained as shown in Figure 19 from April 22, 1920, until late in the summer of 1920, when practically all the load was removed from the panels *R*, *L*, and *Q*. No further changes were made until in November, 1920. Between November 4 and 9 the remaining load was shifted again so as to give the loading shown in the last line of Table 4. The loads placed on panels *H*,

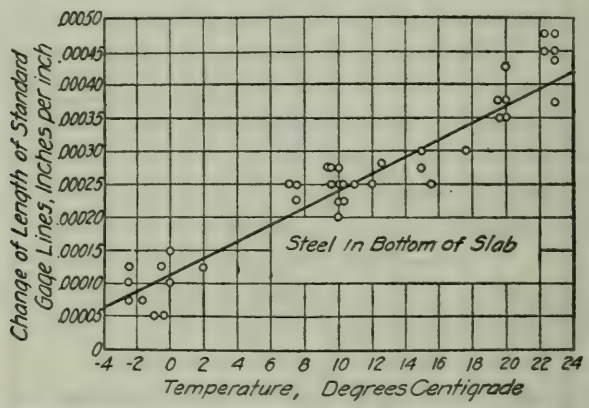

FIG. 12.—*Temperature-deformation curves for small unstressed slabs for April, 1920.*

J, and *K* between November 4 and 9 have remained in position until the present time (October 1, 1921), but most of the live load from all other panels was removed from the slab shortly after November 9.

To furnish loading material for the three panels tested November 4 to 9, bricks were taken from adjoining panels. The stacks shown in Figure 12 were carried as high as seemed practicable and then a layer of 2-inch planking was placed on the top of them. The layer of planking was necessary in order to insure stability of the stacks. For the sake of safety for the men who were working on top of the stacks and in order to secure maximum loads with the least height, the stacks above the planking were made solid; that is, no aisles were provided as in the stacks below the planking. In spite of the effort made to avoid arching it is

FIG. 13.—*View of maximum uniform load.*

FIG. 14.—*Load of April 22, 1920; general view.*

FIG. 15.—*Load of April 22, 1920; close view showing form of loading bricks.*

FIG. 16.—*Final load on panels H, J, and K; view from northwest.*

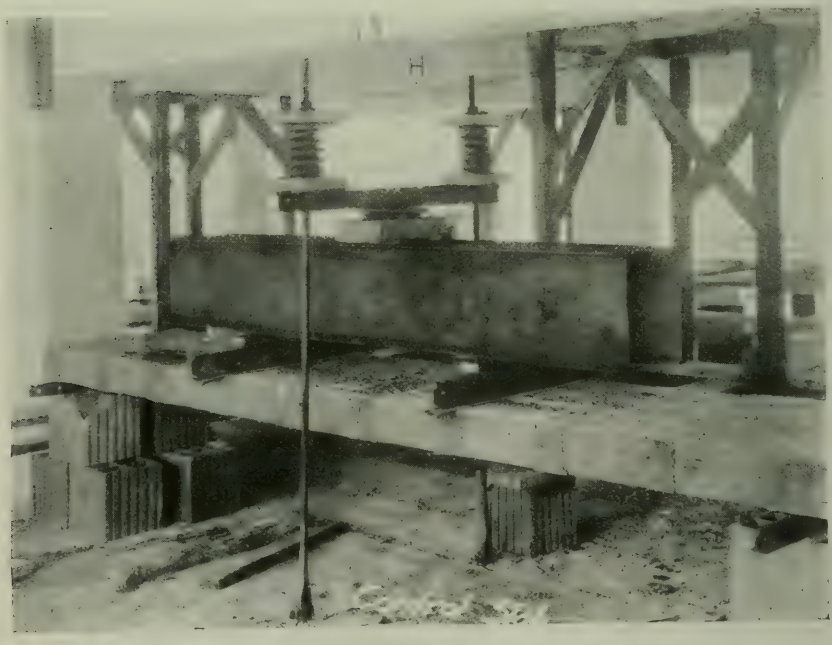

FIG. 17.—*View of control slab under test.*

recognized that the conditions for the greatest loads were such that some arching was present. It is not known how important this arching effect was, but in any case the conclusions regarding the intensity of the shearing stresses and moment coefficients would remain unchanged. Arching would not reduce the shear, and the moment coefficients reported apply to the loads which were distributed in four stacks per panel, with which no appreciable arching can have occurred.[5]

Figure 16 also shows that at one time there was considerable load on other panels besides *H*, *J*, and *K*. In spite of the pre-

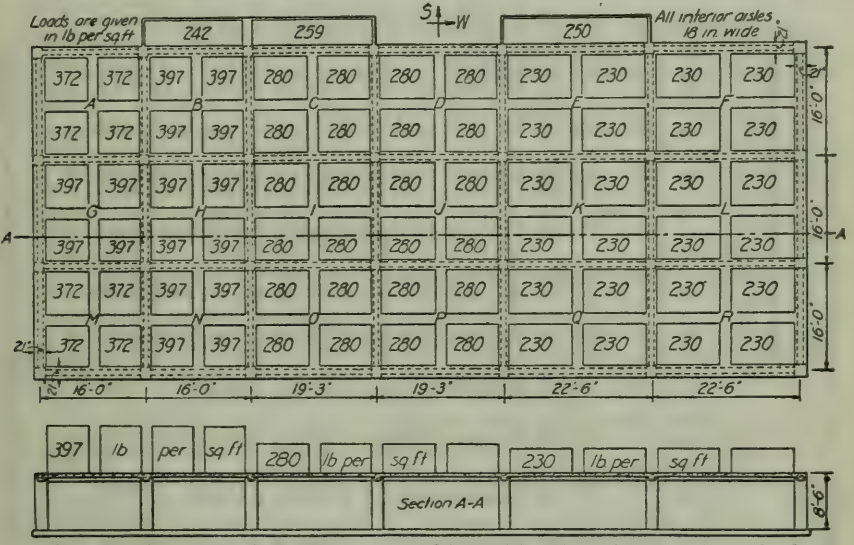

FIG. 18.—*Plan of slab showing areas and intensities of maximum uniform load.*

caution taken to secure maximum loads with minimum heights it was not practicable to carry the loads high enough to cause failure of the slab in any of the panels.

(*c*) CONTROL SLABS.—Control observations included the measurement of deformations in standard gauge lines in the reinforcement, in the concrete, and in the tiles of unstressed slabs of small area, which were of the same thickness and of the same general makeup as the large slab. Readings on these slabs were taken at frequent intervals during the taking of the strain readings on the test slab. Observations of the atmospheric temperature were taken at the same time.

Two slabs termed control slabs, 2 feet, 6 inches wide, 12 feet long, 6 inches thick, and similar in form of construction to the

[5] Under date of June, 1922, it is reported that the loads shown in the last line of Table 4 are causing progressive deflections and opening of cracks in the oblong panels and that complete failure may be approaching, but that the loaded square panel is in good condition.

TABLE 4.—Log of Applied (Live) Loads.

Date.	Applied load in pounds per square foot on—																				
	Panel.																		Cantilever.		
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	B	C	E
Dec. 22, 1919, to Jan. 6, 1920	35	35	37	37	37	37	35	35	37	37	37	37	35	35	37	37	37	37	36	37	36
1920.																					
Jan. 7–9	60	60	65	65	65	65	60	60	65	65	65	65	60	60	65	65	65	65	72	74	72
Jan. 10–11	85	85	92	92	92	92	85	85	92	92	92	92	85	85	92	92	92	92	107	111	108
Jan. 12	110	110	120	120	120	92	110	110	120	120	120	92	110	110	92	120	120	92	143	148	144
Jan. 13	160	160	175	120	120	120	160	160	175	120	120	120	160	160	120	120	120	120	143	148	144
Jan. 14	160	160	175	175	148	148	160	160	175	175	148	148	160	160	120	120	148	148	215	222	215
Jan. 15–16	160	160	175	175	175	175	160	160	175	175	175	175	160	160	175	175	175	175	215	222	215
Jan. 17–18	160	160	175	175	175	202	160	160	175	175	175	202	160	160	175	175	175	192	215	222	215
Jan. 19	160	160	175	175	192	230	160	160	175	175	202	230	160	160	175	175	202	230	215	222	251
Jan. 20	160	160	202	230	230	230	160	160	202	230	230	230	160	160	175	175	230	230	215	222	251
Jan. 21–28	210	210	230	230	230	230	210	210	230	230	230	230	210	210	230	230	230	230	215	222	251
Jan. 29	233	233	230	230	230	230	233	233	230	230	230	230	233	233	230	230	230	230	215	222	251
Jan. 30	279	279	230	230	230	230	279	279	230	230	230	230	279	279	230	230	230	230	250	222	251
Jan. 31–Feb. 1	279	279	230	230	230	230	279	302	230	230	230	230	279	279	230	230	230	230	250	222	251
Feb. 2	325	325	255	255	230	230	325	325	255	255	230	230	325	325	230	230	230	230	250	259	251
Feb. 3	372	372	255	255	230	230	372	372	255	255	230	230	372	372	230	230	230	230	250	259	251
Feb. 4	372	372	280	280	230	230	372	372	280	280	230	230	372	372	280	280	230	230	250	259	251
Feb. 5–Apr. 2	372	397	280	280	230	230	397	397	280	280	230	230	372	397	280	280	230	230	250	259	251
Apr. 3–5	396	362	280	280	230	260	397	397	280	280	230	175	372	397	280	280	230	260	250	259	251
Apr. 6	396	348	253	253	216	260	397	467	335	335	258	175	372	374	253	253	216	260	250	259	251
Apr. 7	396	313	225	240	216	260	397	537	390	362	258	175	373	339	225	240	216	260	250	259	251
Apr. 8–11	396	271	197	197	189	260	397	612	445	445	313	175	372	290	197	197	189	260	250	259	251
Apr. 12–13	396	271	197	197	189	260	345	682	445	445	313	175	372	290	180	197	189	260	250	259	251
Apr. 14–18	396	271	197	197	120	313	298	730	550	445	451	125	372	290	140	197	120	260	250	259	251
Apr. 19	468	.....	106	197	100	370	228	730	605	445	505	72	430	180	92	197	97	260	250	259	251
Apr. 20	590	.....	106	197	.....	370	.....	730	605	445	505	72	468	.....	.....	197	.....	260	250	259	251
Apr. 21	615	146	106	197	.....	370	.....	730	605	.....	505	72	545	.....	.....	360	.....	260	250	259	251
Apr. 22–Sept. 1	615	146	106	197	82	370	76	730	605	192	505	72	545	175	51	525	51	260	250	259	251
Sept. 1–Nov. 4	615	146	106	197	82	370	76	730	605	192	505	38	545	175	51	525	.....	.....	250	259	251
Nov. 8	615	146	79	146	82	370	76	1,413	[1] 430	144	505	38	460	65	51	525	10	17	250	259	251
Nov. 9, 1920, to Oct. 1, 1921	(2)	(2)	(2)	(2)	(2)	(2)	(2)	1,413	(2)	1,184	920	(2)	(2)	(2)	(2)	(2)	(2)	(2)	250	0	0

[1] Load on east half of panel estimated to be 550 lbs./ft.
[2] Loads in all panels except H, J, and K were small on Nov. 9 and have been completely removed since that time, or nearly so.

large slab, were provided in order to determine the effectiveness of the tiles in resisting compressive stresses in this type of construction. Figure 17 is a view of one of these slabs under load. The load was applied by the reaction of two springs which had been previously rated in a testing machine. In the slab test the amount of closure of the springs was measured and the corresponding load was determined therefrom.

The central concrete rib in each of the control slabs was reinforced in the bottom with three ⅝-inch round bars. This gave a much higher percentage of reinforcement than was used in the large

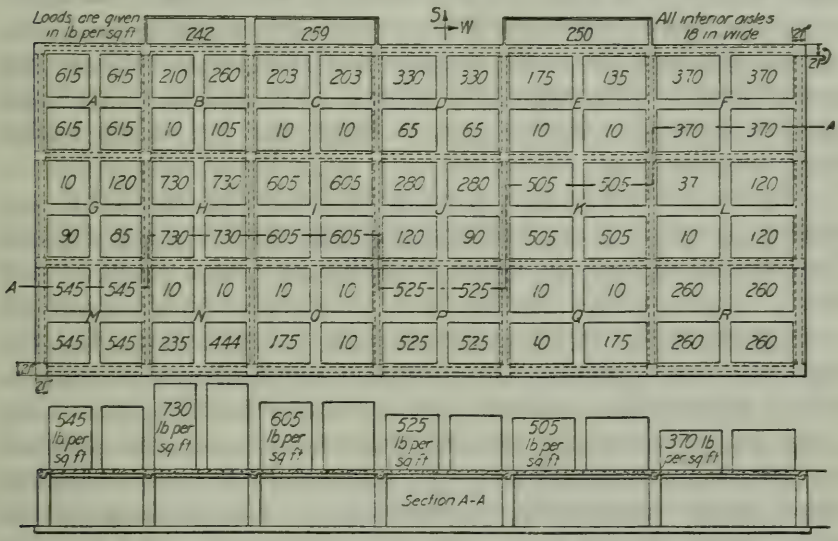

FIG. 19.—*Plan of slab showing areas and intensities for load of April 22, 1920.*

test slab. This high percentage was necessary in order to obtain large deformations in the tiles and concrete before failure.

The axes of the cells of all the tiles were parallel to the span in control slab No. 1. Those of the tiles at mid span in control slab No. 2 were perpendicular to the span. Control slab No. 1 was tested at the same time as the large slab, under loads giving stresses in the reinforcement as nearly as possible the same as the stresses in the negative reinforcement in the large slab. The test of control slab No. 1 extended over a period of 84 days. Figures 22 and 23 show the length of time that the slab was held under successive loads and indicate that with the yielding of the slab the load and the tensile deformation decreased, while the compressive deformations increased slightly. Control slab No. 2 was tested to failure in one day, April 15, 1920, observations being made under different loads before failure.

4. TEST DATA.

The intensities of the load per square foot given throughout this paper were obtained by dividing the total panel load by the area inclosed by the faces of the supporting girders; that is, by the product of the clear spans. The moment coefficients based upon these loads and the measured stresses are about 8 per cent too low because the centers of gravity of the loaded areas fell closer to the supports than the one-fourth point of the clear span. For computing moment coefficients, therefore, a load 8 per cent smaller than that found in this way has been used. This gives about the same results as would be obtained by basing the intensity of the load upon the total area of the panel between the center lines of the supporting girders. The weight of the sand cushion inside the frames used to define the size of the loaded areas was taken as 10 lbs./ft.^{2}

Considerable study was given to determining a basis for correcting the strain gauge readings for changes in the length of gauge lines due to changes in weather conditions. As a result of this study, it was decided that the most satisfactory basis for making corrections in the strain gauge readings was to assume that the readings varied directly in proportion to the temperature changes. All of the readings taken in January and February, 1920, were corrected in accordance with this assumption when the observed air temperatures were below 0° C., and no correction was applied when the air temperature was above zero. This procedure seems to be logical in view of the fact that during that period the slab was at all times covered by ice and snow and for this reason the temperature of the slab itself would not rise above 0° C. even though the air temperature should reach a higher point.

All of the observations taken in April, 1920, were reduced to those which should have been found at 0° C. in accordance with the assumption that readings varied directly in proportion to the changes in air temperature.

Figures 11 and 12 show the relation between the observed air temperature and the change in length of standard gauge lines in the reinforcement, concrete, and tiles of the unstressed slabs. The slope of the inclined portion of the mean lines fitted to the points in both figures represents fairly closely the coefficient of expansion of the materials.

Since the side pieces of the strain gauges used were of invar steel, it was assumed that no changes requiring corrections occurred in those instruments.

Figures 41 to 44 give the load-deformation curves for all panels. On these diagrams tension is plotted to the right and compression is plotted to the left. The open circles indicate deformations in the steel and the solid circles indicate deformations in the concrete.

Figures 45 to 47 give the distribution of deformations in the slab reinforcement in the top of the slab which took stress due to negative moment across the edges of all girders of all panels under the maximum uniform load. The points connected by the broken lines are readings taken after the load had been in place less than three weeks; the solid lines connect readings taken after the load had been in place about nine weeks. Stresses beyond the yield point have been assumed to be the same as the yield-point stress of 54,000 lbs./in.^{2} This stress corresponds to a unit deformation of 0.0018, and for all gauge lines where the yield point was exceeded the unit deformation is shown as 0.0018. To have plotted the full deformation for the gauge lines where the yield point had been exceeded would have led to serious confusion in interpreting the diagram.

Reference to Figure 1 shows that in order to reach a stress appreciably higher than the yield point a very large unit deformation would have been required. In all but a few gauge lines, which were located in panel *R*, the maximum unit deformations were less than 0.003. In those few gauge lines the deformations were so large as to be beyond the range of the strain gauge. Even if the stress was considerably beyond the yield point in those gauge lines, they were so few in number that the conclusions from the test would not be changed.

Figure 48 gives the distribution of deformation at the centers of the spans for the maximum uniform load. Figure 49 gives the distribution of deformation at the centers of typical spans for the load of April 22, the intensity of which is shown in Figure 19.

Figures 50 to 52 give the distribution along the edges of girders of compressive deformations in the concrete due to negative moment in the slab next to the girders. Compressive deformations are plotted upward and tensile deformations are plotted downward.

5. RELIABILITY OF RESULTS.

Because of the unusually severe weather conditions in January and February, extreme precautions had to be taken to secure accurate strain gauge readings and to protect the observation points from damage. The gauge holes in the steel bars on top of the

slab were protected by covering the bar with paper and filling the hole in the concrete above the paper with grease. This procedure generally prevented ice from coming in contact with the bar and avoided the possibility of doing injury to the gauge holes when removing the ice from the holes in the concrete preparatory to taking readings. There were indications that in some cases the steel plugs which were set in the concrete and in the tiles on the upper surface of the slab to provide suitable gauge holes for deformation readings were disturbed in the operation of removing the snow and the ice. This raised a question as to whether much reliance could be placed in the deformations observed in those places and, on this account, no use was made of those readings.

Extremely cold weather also made it difficult for the observers to secure readings in January and February. It required great persistence to obtain a satisfactory set of no-load strain gauge readings. Each observer took as many sets of readings as were necessary to secure satisfactory agreement between at least two consecutive series of readings. In some instances this required five or more series. In all the series of observations taken with the load on the slab check readings were frequently taken. In some series readings were taken for each gauge line twice, or even more times if necessary, to obtain satisfactory check readings.

The possible error in a recorded deformation is made up of the possible error of observation and the possible error in determining the temperature correction. The readings were recorded to the nearest one-half division of the strain gauge dial. It is believed that the error in reading was usually less than one division. It is believed also that the error in determining the temperature correction was in very few cases more than plus or minus two divisions of the dial and was in most cases less than plus or minus one division. One division of the instrument with a 4-inch gauge length corresponds to a unit deformation of 0.00005, equivalent to a stress of 1,500 lbs/in.^{2} in the reinforcement. It is believed, furthermore, that the sum of the error of observation and the error in applying the temperature correction for the readings taken in January and February seldom exceeded plus or minus three divisions of the instrument and that, for the majority of cases, the total error was much less than this.

Due to the more favorable weather in April, it is believed that the error in readings taken at that time was considerably less than the error in the readings taken in January and February.

The total error in the corrected observations probably did not often exceed plus or minus one division of the instrument, which is equivalent to a stress of 1,500 lbs./in.^{2} in the reinforcement.

Obviously the stresses reported in this paper must be based upon the average unit deformation measured in a gauge length of 4 inches. Since in general the unit deformation is not uniform over the gauge length the actual stresses will be somewhat greater than those reported. The lack of uniformity of deformation will be due mainly to variation of moment over the gauge length and to the occurrence of cracks within the gauge length. The error due to the first of these causes will be relatively small. The error due to the fact that the stress is larger at a crack than elsewhere within the gauge length will be more important. The proportionate amount of the error so introduced will depend upon the size of the bar, the bond resistance between the concrete and the bar, the length of the gauge line, and the intensity of the stress in the bar. With a ½-inch bar and a 4-inch gauge length the error might be 20 per cent or more when the observed average unit deformation corresponds to a stress of 10,000 lbs./in.^{2} or less. With an observed stress of 40,000 lbs./in.^{2} or more the error may be as much as 5 per cent and probably not more than 10 per cent. The effect of such error will be to make the stress appear less than it is.

III. RESULTS OF TESTS.

1. DEFORMATIONS IN TILES, CONTROL SLABS, AND LARGE TEST SLAB.

Figures 20 and 21 give the deformations for each gauge line in the tiles and in the concrete in control slabs 1 and 2, respectively, under different total loads and show that the tiles resisted an important part of the compressive stresses. At a given load the longitudinal deformation in the concrete rib was somewhat greater than that at a position immediately adjoining it in the tile. From that point outward to the edge of the slab the longitudinal deformation was approximately uniform. This was true of both control slabs. The first load applied caused cracks in the under surface of the slab. The total load shown on each curve in Figures 20 and 21 is the sum of the weight of the slab and the applied load.

Figures 23 and 24 show the average tensile deformation in the reinforcement and the average compressive deformation in the concrete and the tiles for control slabs 1 and 2, respectively,

under different applied loads. The ratio of the deformation in the tiles to the deformation in the concrete was computed from these averages and is shown in Figure 25. The numbers attached to the points in Figures 22 and 25 indicate the order in which the observations were made.

The results for the tests on the two control slabs were very consistent. The average ratio of deformation in the tiles to the deformation in the concrete for all applied loads was 0.727 for slab No. 1 and 0.741 for slab No. 2. The ratios for different ap-

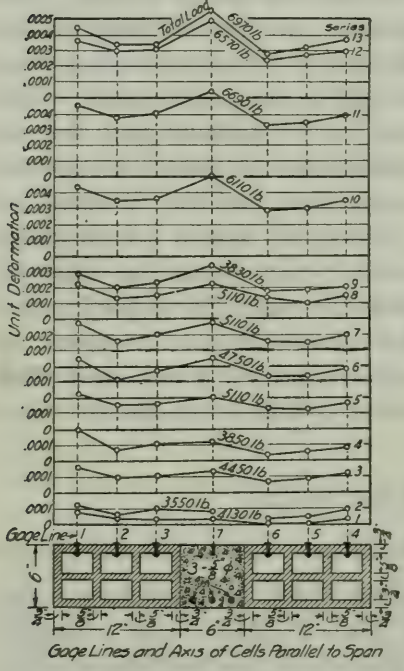

FIG. 20.—*Distribution of compressive deformations across top of control slab No. 1.*

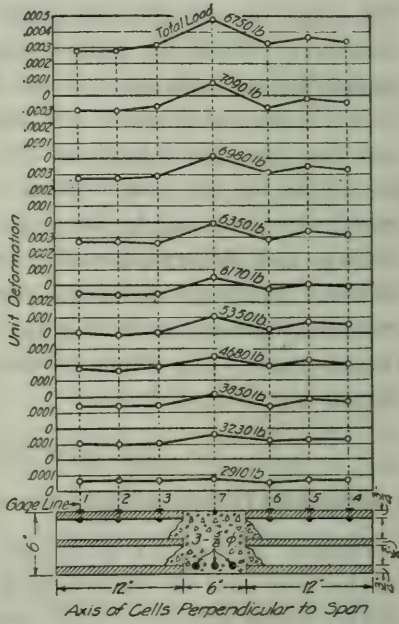

FIG. 21.—*Distribution of compressive deformations across top of control slab No. 2.*

plied loads are more nearly uniform for control slab No. 2 than for slab No. 1, due probably to the fact that for slab No. 2 all observations were made on the same day. The ratios obtained for control slab No. 1 were, in general, lower after the applied load had remained on the slab for a considerable length of time than the ratios obtained from observations taken immediately after the load was applied.

For the large slab, data for the comparison of the deformations in the tiles with the deformations in the concrete were available for two loads. The comparison can not be made directly, how-

ever, since the gauge lines on the concrete in the large slab were located near the edge of the girders while those in the tiles were at least 7 inches farther from the point of the maximum negative

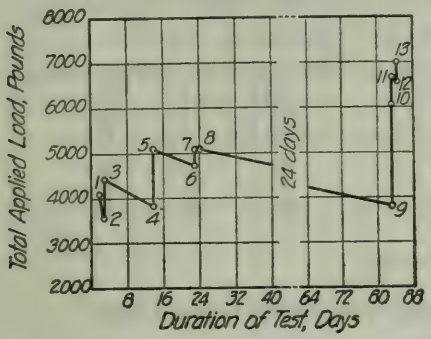

FIG. 22.—*Duration-of-load curve for control slab No. 1.*

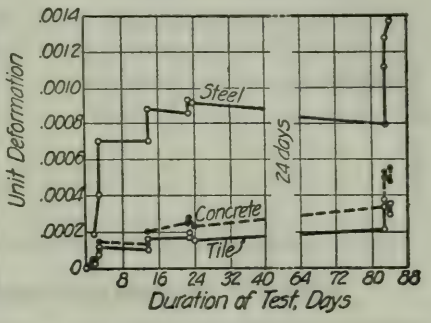

FIG. 23.—*Deformations for control slab No. 1 at successive stages of the test.*

moment. Assuming that the unit deformation at any point in an element of the large slab was directly proportional to the distance from the point of zero stress, the deformations in the concrete

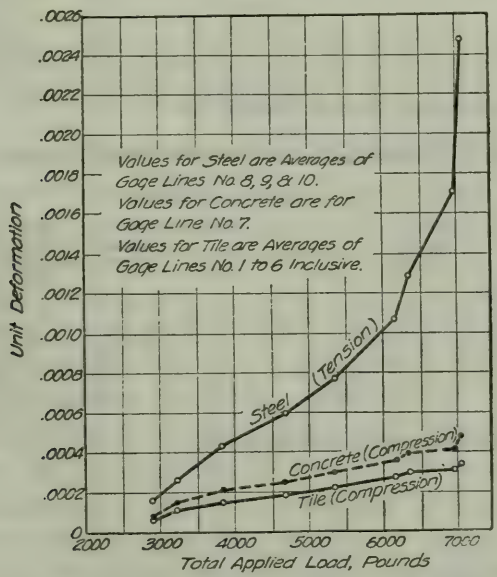

FIG. 24.—*Load-deformation curves for control slab No. 2.*

were corrected so as to make them comparable with the observed deformations in the tiles. Using the available data for the two loads, the ratio of the mean deformation in the tiles to the corrected mean deformation in the concrete was found to be 0.717.

TABLE 5.—Deflection in Square Panels under Constant Load.

Panel.	Applied load.	Time under constant load.	Deflection.	
			After one day.	Final.[1]
	Lbs./ft.[2]	Days.	Inches.	Inches.
H (interior)	160	7	0.00	0.00
A (exterior)	160	7	.08	.10
H	210	7	.00	.00
A	210	7	.12	.12
H	397	52	.09	.22
A	372	53	.37	.70
H	730	30	.55	.68
A	615	23	1.36	1.52

[1] At end of period indicated as "Time under constant load."

TABLE 6.—Deflection in Intermediate Panels under Constant Load.

Panel.	Applied load.	Time under constant load.	Deflection.	
			After one day.	Final.[1]
	Lbs./ft.[2]	Days.	Inches.	Inches.
I (interior)	230	11	0.10	0.11
P (exterior)	230	13	.14	.17
I	280	55	.15	.26
P	280	55	.28	.44
I	605	25	.86	1.15
P	525	22	1.19	1.52

[1] At end of period indicated as "Time under constant load."

TABLE 7.—Deflections in Long Panels under Constant Load.

Panel.	Applied load.	Time under constant load.	Deflection.	
			After one day.	Final.[1]
	Lbs./ft.[2]	Days.	Inches.	Inches.
K (interior)	230	69	0.11	0.11
F (exterior)	230	69	.39	.73
K	505	25	1.04	1.32
F	370	25	1.33	1.72

[1] At end of period indicated as "Time under constant load."

While this average agrees very closely with the ratio which was found between the deformations in the tiles and the deformations in the concrete in the control slabs, the variations between individual values for different parts of the slab were considerable.

The modulus of elasticity of the tiles was, in general, more than 1.5 times the modulus of elasticity of the concrete. If the deformation in the tiles be taken as 0.70 times the simultaneous deformation in the adjoining concrete, the compressive unit stress in

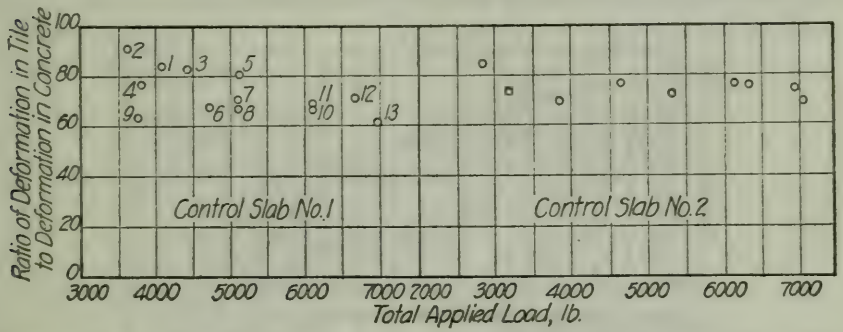

FIG. 25.—*Ratios of unit deformation in tiles to unit deformation in concrete for control slabs.*

the tiles must have been at least 1.5 times 0.70, or 1.05 times as great as the unit stress in the concrete.

2. DEFLECTIONS FOR SQUARE PANELS.

Figure 26 gives the deflections at the centers of the square panels and the loads which produced these deflections. In panel *A* the deflection was 0.12 inch, or less than 1/1,500 of the clear span under an applied load of 210 lbs./ft.², of which over two-thirds had been in place for 17 days. Under the same unit load the deflections in the other square panels were less than this and in panel *H* no deflection at all was detected.

There was, in general, a slight increase in deflection during the first day that the applied load of 210 lbs./ft.² was in place, but there was no further increase in deflection in any of the square panels due to that load remaining in place 6 days longer. As far as can be judged from the data available the slab behaved in the same manner under the loads of 160 and 35 lbs./ft.² as for the load of 210 lbs./ft.² No other load below the maximum uniform load was sustained long enough to give a basis for judging the effect of a continued static load on the deflections.

For the loads exceeding 210 lbs./ft.^{2} there appears to have been an increase in deflection as long as the load remained in place. It is not entirely certain that this is true since the readings of deflections were not taken with sufficient frequency in all of the panels to make certain that the entire amount of deflection did not take place soon after the load was applied. Of the square panels there was only one which may properly be termed an interior panel. The rate of deflection under constant load was less for this panel than for the exterior panels.

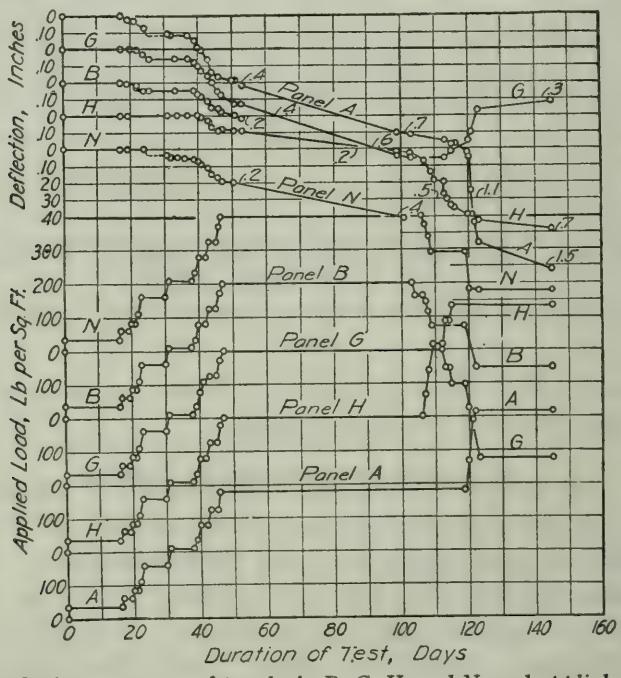

FIG. 26.—*Deflections at centers of panels A, B, G, H, and N, and applied loads on the panels.*

When load was shifted from panels *B*, *G*, and *N* to panels *A*, *H*, and *M*, the deflections decreased in the former and increased in the latter until the greatest deflection reached in any square panel previous to the November loading occurred in panel *A* (a corner panel) under a uniform live load of 615 lbs./ft.^{2} This deflection was 1.36 inches after the load had been in place one day and 1.52 inches after the load had been in place 23 days. The maximum deflection for an interior square panel occurred in panel *H* under a uniform live load of 730 lbs./ft.^{2} This deflection increased from 0.55 inch within 1 day to 0.68 inch after the load

had been in place for 30 days. Table 5 summarizes the principal deflections in the square panels. In Tables 5, 6, and 7 the deflection "after 1 day" is the deflection which was found after the load had been in place 1 day and the "final deflection" is that which was found at the end of the recorded "time under constant load."

3. DEFLECTIONS FOR INTERMEDIATE-SIZE PANELS.

Figure 27 gives the deflections at the center of the intermediate-size panels and the loads which produced these deflections.

Table 6 shows the effect of long-continued load on the deflections of typical panels.

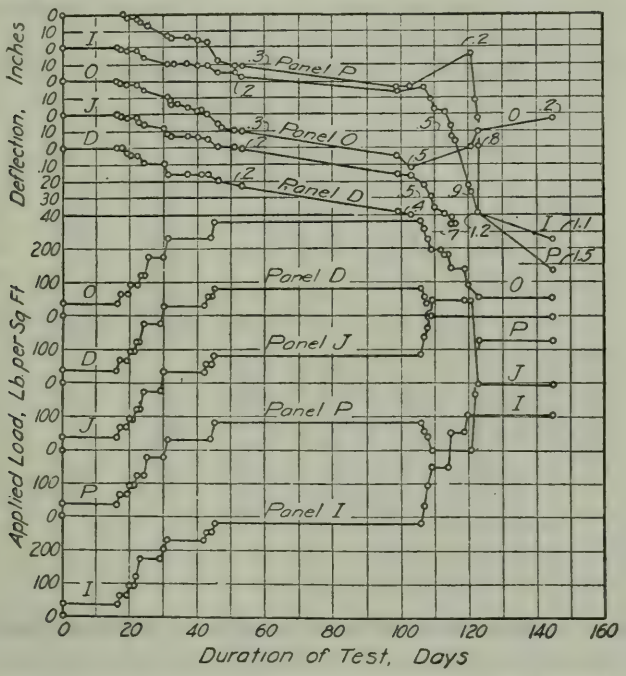

FIG. 27.—*Deflections at centers of panels D, I, J, O, and P, and applied loads on the panels.*

For the lower loads shown the increase in deflection under constant load was slight, even though the load was high in comparison with what in Section II, 2, are termed the design loads. For the larger loads the increase in deflection was considerably greater than for the smaller loads. The exterior panels showed a slightly greater rate of increase in deflection under constant load than the interior panels. The deflections shown for panels *I* and *P* under loads of 605 and 525 lbs./ft.^{2}, respectively, were the largest deflections found for panels of the intermediate size.

TABLE 8.—Recovery from Deflection upon Removal of Load from Exterior Panels.

Panels.	Applied load.	Deflection.	Portion of applied load removed.		Recovery from deflection.		Recovery per 1 per cent load removed.
	Lbs./ft.²	Inch.	Lbs./ft.²	Per cent.	Inch.	Per cent.	Per cent.
G (square)	397	0.65	321	81.0	0.33	51	0.63
O (intermediate)	280	.52	229	82.0	.29	56	.68
E (long)	230	.31	148	64.0	.34	110	1.71
L (long)	230	.53	158	69.0	.45	85	1.24

TABLE 9.—Distance from Surface of Slab to Surface of Slab Reinforcing Bars.

[Values (a) and (b) represent independent measurements at different places in the panel.]

Panel.	At positions of negative moment.				At positions of positive moment.			
	Over exterior girders.		Over interior girders.		East-and-west bars.		North-and-south bars.	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
A	2.25		1.00		1.37	1.25	1.19	0.75
B					1.00	1.12	.69	.69
C	1.12				1.37	1.37	.81	.81
D	1.12				1.43	1.37	.93	.87
E	1.87	1.75			1.43	1.37	.81	.87
F	1.12	2.00			1.19	1.31	.87	.75
G			1.25	0.75	1.25	1.25	.75	.69
H					1.12	1.19	.56	.69
I			.75	1.00	1.19	1.19	.75	.87
J					1.19	1.37	.93	.87
K			1.00	1.00	1.37	1.43	.93	.75
L			.87	1.37	1.25	1.19	.69	.62
M	1.50	1.25	1.00	.87	1.19	1.12	.69	.81
N					1.25	1.12	.75	.81
O	1.50	1.00			1.37	1.19	.75	.81
P	1.62	1.00	1.00	1.00	1.25	1.19	.81	.69
Q	1.12		1.25		1.69	1.56	.93	.93
R	1.12		1.50		1.31	1.56	.93	.75
Average	1.42		1.04		1.29		0.80	

TABLE 10.—Values of *d* and *jd* Used in Computation of Moment Coefficients.

Position or designation.	*d*.	*jd*.
Negative moment	4.75	4.28
Positive moment, north-and-south	5.0	4.50
Positive moment, east-and-west	4.5	4.05

4. DEFLECTIONS FOR LONG PANELS.

Figure 28 gives the deflections at the centers of the long panels and the loads which produced these deflections.

Table 7 shows the effect on the deflections in certain panels of allowing the load to remain in position for a considerable length of time.

Approximately the same relation is seen between the deflections in long exterior panels and those in long interior panels

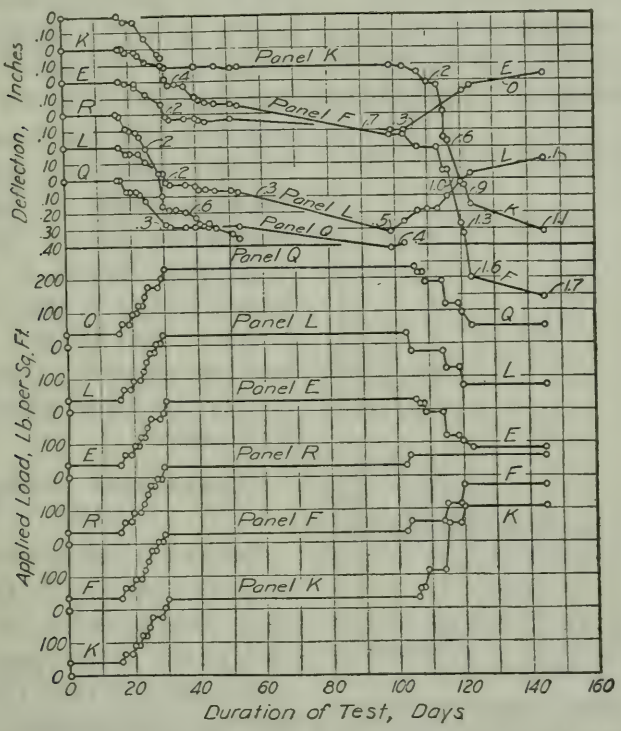

FIG. 28.—*Deflections at centers of panels E, F, K, L, Q, and R and applied loads on the panels.*

as was found in the comparison of exterior and interior square and intermediate-size panels. The effect on long panels of standing under constant load was not greatly in excess of the effect for square and intermediate-size panels. When the fact is taken into account that the safe working load would be considerably different for the panels of different size, it does not appear that the effect of long-continued load was any greater for the long panels than for the others.

5. RECOVERY FROM DEFLECTION UPON REMOVAL OF LOAD.

Data on the effect of partial removal of load on deflection are available for a few panels. These data are given in Table 8. The loads on these panels and surrounding panels before and after the load was changed are given in Figures 18 and 19.

The recovery in the panels referred to in Table 8 was assisted by the increase in load on the adjacent panels simultaneously with the decrease in load on panels, *G*, *O*, *E*, and *L*. The ratios of the loads on panels *G*. *O*, *E*, and *L*, respectively, to the loads on the corresponding heavily loaded adjacent panels do not vary so greatly but that a comparison of the amounts of recovery is of some value. Table 8 shows that proportionally the recovery was least for the square panel reported upon and greatest for the long panels. A reference to Figure 39 shows that there were fewer cracks in the long panels *E* and *L* than in panels *G* and *O*, and for that reason it may be expected that the recovery for these panels would be greater.

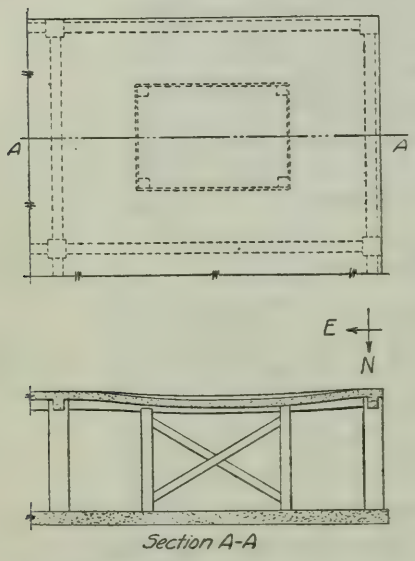

FIG. 29.—*Panel F resting on auxiliary posts.*

6. DEFLECTION UNDER FINAL LOAD.

Before the slab was first loaded in December, 1919, four posts were placed under the slab in each panel. These posts were of such a length that their upper ends came within about 3 inches of the bottom of the slab. These posts were provided in order to insure safety in case complete failure should occur with the slab under load. Up to April 22, 1920, the end of the first test, none of the panels had deflected sufficiently to cause the slab to rest upon the posts. Within a few weeks it was noted that the slab of panel *F* had deflected so that it rested upon two of the posts. The other two posts were free of the slab. Figure 29 shows approximately in plan the position of the posts and in elevation the original and deflected positions of the slab. The locations of the posts in the other panels were approximately the same as those in panel *F*.

After the completion of the April test the deflection apparatus had been removed and the further deflection of the slab could not be determined except by measurement of the curvature of its under surface, assuming that originally it was a plane surface. By this means the deflections shown in Figure 30 for November 4 and 8 were found just previous to the November test.

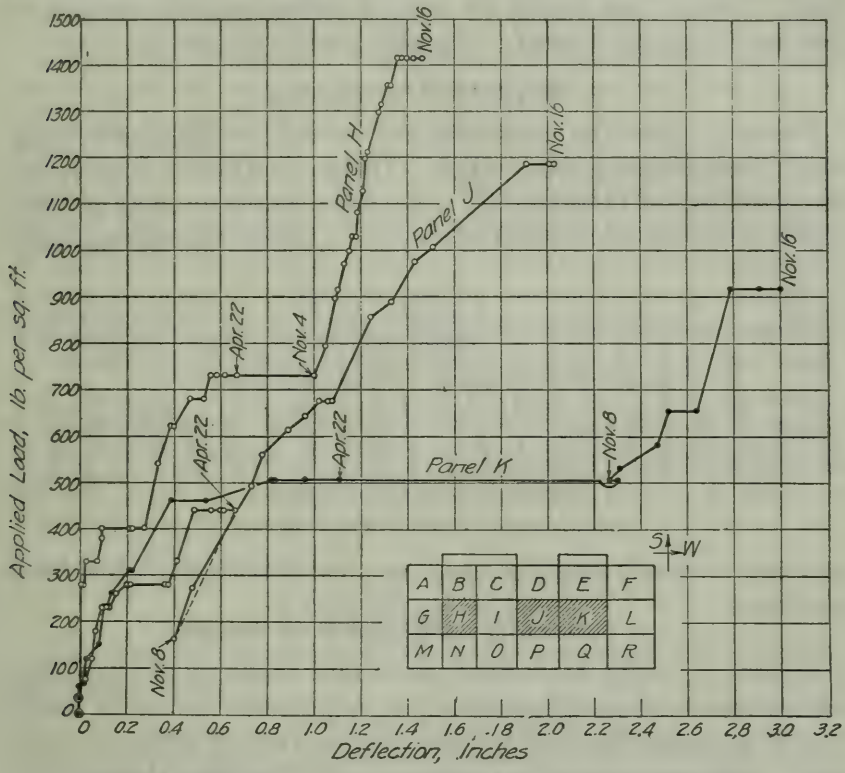

FIG. 30.—*Deflections of panels H, J, and K, up to November, 1920.*

Before the final loading (applied in November, 1920) the thread and mirror apparatus for measuring deflections was replaced in the panels to which more load was applied and during the test additional deflections were observed. The error of these deflection readings is believed to be not more than plus or minus 0.01 inch. The error of determining the deflections by means of the curvature of the slab surface before the application of load in November, 1920, may be as much as plus or minus 0.1 inch.

The deflections for panels *H*, *J*, and *K* up to the middle of November are given in Figure 30. Apparently the deflection at the center of panel *H* had increased from 0.68 inch at the end of

the April test to about 1.0 inch at the beginning of the November test. The deflection in panel *J* had changed very little, but that in panel *K* had increased about 1.2 inches between the April and the November tests. In view of the fact that the live load on the slab during this time was more than 10 times as great as the "design loads" given in Section II, 2, this increase in deflection is small. For all the panels the rate of deflection with increase of load was about the same for the high load as for the low load.

7. DEFLECTION OF GIRDERS.

Figure 31 gives the load-deflection curves for the girders upon which measurements were taken. These deflections are given for the period up to February 10, 1920, when the maximum uniform load had been in place about two weeks. Deflection readings after

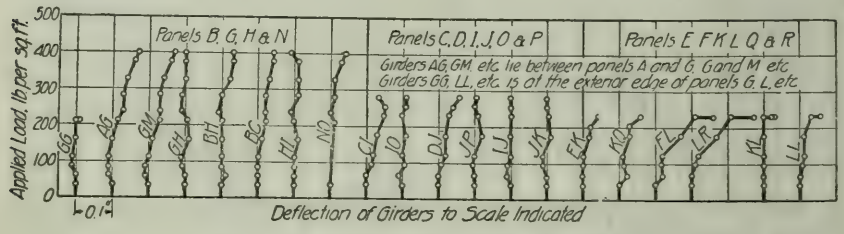

FIG. 31.—*Load-deflection curves for girders.*

this time were not taken because the observation points had been disturbed.

8. TORSIONAL RESISTANCE OF GIRDERS.

Figures 45 to 47 show that the deformations in the negative reinforcement across the edges of the wall girders were very small. This is an indication that the wall girders twisted without giving much resistance to torsional moment. The fact that the negative moment coefficients (see Fig. 32) for the slab over the girders which were one panel length or width away from the wall girder were no greater, in general, on the edge of the girder toward the wall than on the edge farther from the wall, points toward the same conclusion. The torsional resistance of the girder is the only thing which should introduce any appreciable difference between the stresses at these two points and since the difference in stresses was too slight to be detected the torsional resistance of the girder could not have been large.

If there were no torsional resistance in the wall girders, the lack of fixity of the slab at the wall would be expected to be accompanied by high stresses due to positive moment at the middle of

the wall span. The average stresses due to positive moment in the square and the long wall panels were greater than corresponding averages for interior panels, while in the intermediate size wall panels they were less than in the interior panels. The average, however, for wall panels of all sizes was almost the same as that for interior panels. This seems to be in contradiction to the indications of the preceding paragraph. Possibly the inconsistency is only apparent and is due to the fact that at positions of positive moment and at sections along the wall girders the stresses were generally so low that the concrete was not extensively cracked. This would vitiate a comparison of moments based upon measured steel stresses. That this may be the explanation is indicated by the fact that the greatest excess of stress due to positive moment in wall panels over that in interior panels is found by using panel *R* in the comparison. The concreting was of a poorer quality in that panel than elsewhere, and such differences would be magnified.

9. MEASURED DEPTH TO REINFORCEMENT.

The depth from the tension surface of the slab to the surface of the reinforcement was measured in representative positions in various parts of the slab. The depths are shown in Table 9. The depths to the centers of the bars were used for the computations of resisting moment.

10. MOMENT COEFFICIENTS.

The moment coefficients, *K*, were computed by using the following relation:

$$M = KWl = Afjd \text{ where}$$

M = total resisting moment offered by the observed tensile stresses in the reinforcement which crossed one edge of the panel (for negative moment) or the center line of the panel (for positive moment).

W = 0.92 of the sum of the live and dead load within the panel area (see Sec. II, 4); the dead load was taken as 50 lbs./ft.^{2};

l = clear span in the direction of the short side (180 inches);

A = total sectional area of reinforcement crossing an edge or a center line of the panel considered;

f = observed tensile stress in the reinforcement plus an allowance of 2 per cent for the dead load stress in the reinforcement [6];

jd = moment arm of the resisting couple.

[6] The stresses used in computing the average coefficients given in Table 15 range probably from 30,000 to 50,000 lbs./in.^{2} Therefore, the stress allowed for dead-load ranges from 600 to 1,000 lbs./in.^{2} For a discussion of stresses before cracking of the concrete, see Westergaard and Slater, "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, p. 478; 1921.

For positions of negative moment the distance d from the compression surface of the slab to the center of the reinforcement was determined from the average measurements taken at the edges of the girders in a number of places on the slab and was found to be 4.71 inches. The value used in computations was 4.75 inches.

The value used for j was 0.9 and for jd 4.28 inches. This was obtained from the relation

$$jd = d - \frac{1}{3} kd,$$

in which kd, the depth from the compression surface to the neutral axis, was determined by the ordinary methods from the measured deformations; that is, by assuming that the deformations varied directly with the distance from the neutral axis. This value of jd represents the average for all panels for the positions where maximum deformations occurred in the reinforcement in the top of the slab and in the concrete below.

The moment coefficients given in this paper represent a measure of the moment resisted by the stress in the reinforcement. It is recognized that this stress will not account for all the moment in the slab. A study of the results of this test as a basis for an estimate of the total moments has been made elsewhere.[7]

The same considerations as those which in Section III, 16, are stated as a reason for expecting the tiles to form an integral part of the slab in resisting the shearing stress, also constitute a reason for expecting an appreciable part of the moment to be carried in other ways than by tension in the reinforcement, just as has been found in other tests of concrete slabs. In the basing of coefficients for design upon the values here given account must be taken of this fact.

The values of the observed deformations after the load had been in place about nine weeks were used as the basis of the computations of jd. The value of jd as computed from deformations observed after two weeks under load was 4.35 inches. The decrease in the value of jd with long-continued loading will help to account for the corresponding increases in tensile stress in the reinforcement. However, it is probable that progressive cracking of the concrete played a more important part in causing the increase in the tensile stress than did the decrease in jd.

[7] Westergaard and Slater, "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, p. 495–500; 1921.

The values of d and jd for positions of positive moment were determined similarly to those for negative moment. The values for both positions are given in Table 10. For both control slabs the value of jd as computed from deformations for all loads was 4.35 inches.

Values for the stress, f, for use in the computations were obtained by drawing symmetrical curves which would conform as closely as possible to the points plotted to show the distribution of deformations under various loads. (See Figs. 45 to 49.) Each curve was fitted to the points in such a way that the area between the zero line of deformations and the curve which was fitted to the plotted points would be equal to the area between the zero line of deformations and the straight lines connecting the points. The methods of drawing the curves is illustrated in Figure 45. The stress represented by the vertex of each one of these curves was used as the f of the resisting moment equation and is called the "weighted maximum stress". These weighted stresses are given in Tables 11 and 13. Using the weighted maximum stress instead of the average stress to determine the moment M gives a larger moment than the summation of the individual moments of the stresses in the respective reinforcing bars.

Coefficients of bending moment have not been computed from deformations observed in the concrete on account of uncertainty as to the intensity of the stress in the concrete. Numerous tests [8] have shown that the deformations in concrete change enough, under long-sustained constant load, to make it impossible to determine a fixed value of the modulus of elasticity. Thus, the average deformations in the concrete in the sections of the slab indicated in Figures 50 to 52 showed increases varying from practically nothing to more than 200 per cent of the deformation at the beginning of the period.

It was found that the average increase in deformation in the concrete under long-continued load was considerably greater than the average increase in the deformation in the reinforcement during the same period.

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[8] (*a*) F. R. McMillan, "Shrinkage and time effect in reinforced-concrete" Studies in Engineering, No. 3, Univ. of Minnesota; March, 1915.

(*b*) Almon H. Fuller and Charles C. More, "Time tests of concrete," Proc. Am. Concrete Inst., 12, p. 302; 1916.

(*c*) Earl B. Smith, "The flow of concrete under sustained loads," Proc. Am. Concrete Inst., 12, p. 317; 1916, and 13, p. 99, 1917.

11. NEGATIVE MOMENTS IN SLAB.

The stresses in the negative reinforcement observed after the load had been in place about nine weeks were used as a basis for the calculations of moment coefficients. These stresses were considerably higher than those observed after the load had been in place about two weeks. The effect of the load remaining in place for the longer period was to increase the average of the weighted maximum stresses by 38 per cent for the square panels, 57 per cent for the intermediate-size panels, and 23 per cent for the long panels. In some places, as may be seen in Figures 45 to 47, the yield point of the reinforcement had been reached.

Table 11 gives the moment coefficients as computed from the weighted maximum stresses in the reinforcement crossing the

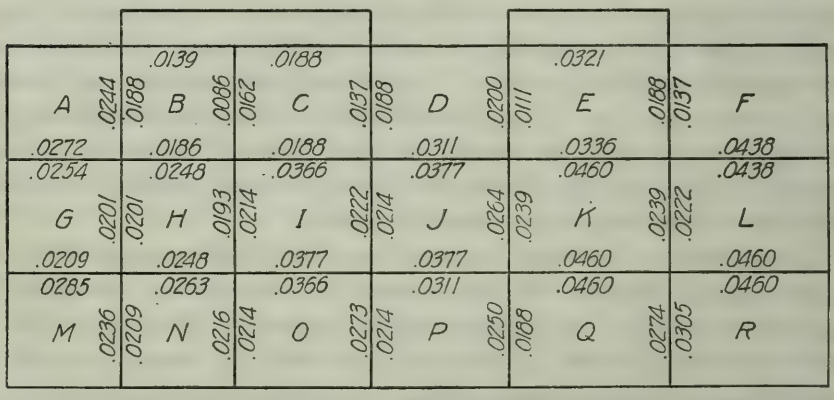


FIG. 32.—*Coefficients of negative moment with maximum uniform load in place 55 to 73 days.*

edges of the panels. These coefficients are shown in Figure 32 along the panel edges to which they apply.

In Table 11 the coefficients are classified as for either interior or exterior panels. A moment is classified as for an exterior panel if it is computed from the stress across the edges of a girder one panel length (or width) removed from a wall girder. For this purpose a cantilever is considered as having the same effect as a panel.

In Figures 33 and 34 the coefficients of negative moment for the panels are shown as ordinates and the ratios of length to width of panels as abscissas. The broken lines in the figures represent mean coefficients for like edges. The averages of the

TABLE 11.—Weighted Maximum Tensile Stresses in Slab Reinforcement and Resulting Coefficients of Negative Moment.

SQUARE PANELS.

Panel.	Applied live load.	Gauge lines considered.	Weighted maximum stress.		Moment coefficients computed from weighted maximum stresses.			
			Load in place, 2 to 21 days.	Load in place, 55 to 73 days.	Load in place, 2 to 21 days.		Load in place, 55 to 73 days.	
					Interior panel.	Exterior panel.	Interior panel.	Exterior panel.
	Lbs./ft.²		Lbs./in.²	Lbs./in.²				
A	372	126–131	33,000	44,500	.....	0.0180	.....	0.0244
		132–137	47,000	51,000	.....	.0255	.....	.0272
B	397	120–125	12,000	27,000	.....	.0062	.....	.0139
		126–131	15,000	16,500	0.0077	.....	0.0086	.....
		132–137	37,500	36,000	.0194	.....	.0186	.....
		138–143	24,000	37,500	.....	.0121	.....	.0188
G	397	120–125	37,500	49,500	.....	.0193	.....	.0254
		126–131	28,500	39,000	.....	.0147	.....	.0201
		132–137	27,000	40,500	.....	.0139	.....	.0209
H	397	120–125	31,500	48,000	.0163	.....	.0248	.....
		126–131	19,500	37,500	.0101	.....	.0193	.....
		132–137	36,000	48,000	.....	.0186	.....	.0248
		138–143	27,800	39,000	.....	.0143	.....	.0201
M	372	120–125	49,500	52,500	.....	.0270	.....	.0285
		126–131	27,000	43,500	.....	.0147	.....	.0236
N	397	120–125	35,000	51,000	.....	.0180	.....	.0263
		126–131	26,300	42,000	.0136	.....	.0216	.....
		134–138	30,000	40,500	.....	.0155	.....	.0209
Average					.0134	.0167	.0186	.0227

INTERMEDIATE PANELS—SHORT SPAN.

C	280	120–127	15,000	25,500	.....	0.0111	.....	0.0188
		135–140	19,500	25,500	0.0145	.....	0.0188	.....
D	280	135–140	40,500	42,000	.....	.0300	.....	.0311
I	280	121–126	31,500	49,500	.0233	.....	.0366	.....
		135–140	33,800	51,000	.....	.0250	.....	.0377
J	280	121–126	33,000	51,000	.....	.0247	.....	.0377
		135–140	37,500	51,000	.....	.0278	.....	.0377
O	280	121–126	34,500	49,500	.....	.0255	.....	.0366
P	280	121–126	30,000	42,000	.....	.0222	.....	.0311
Average					.0189	.0238	.0277	.0330

INTERMEDIATE PANELS—LONG SPAN.

C	280	128–133	22,500	24,000	0.0128	.....	0.0137	.....
		142–147	12,000	28,500	.0068	.....	.0162	.....
D	280	128–133	26,300	35,000	.0150	.....	.0200	.....
		142–147	18,000	33,000	.0103	.....	.0188	.....
I	280	128–133	15,000	39,000	.0086	.....	.0222	.....
		142–147	18,000	37,500	.0103	.....	.0214	.....
J	280	128–133	19,500	46,500	.0111	.....	.0264	.....
		142–147	34,500	37,500	.0197	.....	.0214	.....
O	280	128–133	18,500	48,000	.0107	.....	.0273	.....
		142–147	25,500	37,500	.0146	.....	.0214	.....
P	280	128–133	19,500	44,000	.0111	.....	.0250	.....
		142–147	28,200	37,500	.0161	.....	.0214	.....
Average					.0123	.....	.0213	.....

TABLE 11.—Weighted Maximum Tentile Stresses in Slab Reinforcement and Resulting Coefficients of Nagative Moment—Continued.

LONG PANELS—SHORT SPAN.

Panel.	Applied live load.	Gauge lines considered.	Weighted maximum stress.		Moment coefficients computed from weighted maximum stresses.			
			Load in place, 2 to 21 days.	Load in place, 55 to 73 days.	Load in place, 2 to 21 days.		Load in place, 55 to 73 days.	
					Interior panel.	Exterior panel.	Interior panel.	Exterior panel.
	Lbs./ft.²		Lbs./in.²	Lbs./in.²				
E	230	120–128	36,000	37,500	.....	0.0309	.....	0.0321
		135–143	36,000	40,500	0.0309	.....	0.0336	.....
F	230	135–143	44,300	51,000	.....	.0379	.....	.0438
K	230	120–128	44,500	53,500	.0380	.....	.0460	.....
		135–143	46,500	53,500	.....	.0399	.....	.0460
L	230	120–128	38,500	51,000	.....	.0330	.....	.0438
		135–143	52,500	53,500	.....	.0450	.....	.0460
Q	230	120–128	42,000	53,500	.....	.0360	.....	.0460
R	230	120–128	48,000	53,500	.....	.0411	.....	.0460
Average					.0344	.0376	.0398	.0434

LONG PANELS—LONG SPAN.

E	230	129–134	25,500	33,000	.....	0.0146	.....	0.0188
		144–149	11,000	19,500	0.0063	.....	0.0111	.....
F	230	144–149	27,000	24,000	.....	.0154	.....	.0137
K	230	129–134	37,500	42,000	.....	.0214	.....	.0239
		144–149	31,500	42,000	.0180	.....	.0239	.....
L	230	144–149	37,500	39,000	.....	.0214	.....	.0222
Q	230	129–134	42,000	48,000	.....	.0240	.....	.0274
		144–149	16,000	33,000	.0091	.....	.0188	.....
R	230	144–149	42,000	53,500	.....	.0240	.....	.0305
Average					.0112	.0201	.0179	.0227

coefficients for interior and exterior panels for the square, intermediate, and long panels are given in Table 16. The coefficients of negative moments for the short span showed a marked increase with the increase in ratio of length to width of panel, while the coefficients for the long span changed only slightly with the increased ratio of length to width.

The average moment coefficient for exterior panels was greater in all cases than the corresponding coefficients for interior panels. The ratios of the negative bending moments due to the observed stresses for exterior panels to those for interior panels are given in Table 12.

An examination of the data shows that without exception the negative moments accounted for by the stress in the steel even for the square panels were greatest in the north-and-south direction. The average of all the moment coefficients given in Table

11 for the north-and-south direction is 27 per cent greater than the average for the east-and-west direction. It is not known whether this difference should be taken to indicate that a larger proportion of the load was carried to the girders on the north-and-south margins of the panels or that the concrete and the tiles assisted less in carrying the tensile stresses in the north-and-south direction than in the east-and-west direction. The tiles in all panels were laid with the axes of their cells extending in the north-and-south direction, and the participation of the tiles in resisting tensile stresses in that direction would come mainly through adhesion between the tile and the concrete. For the

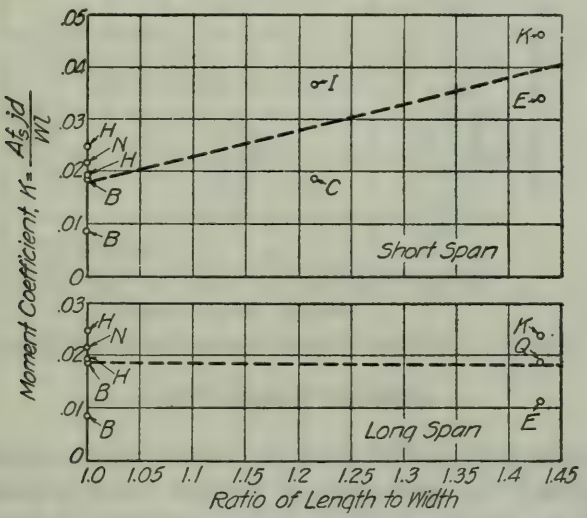


FIG. 33.—*Coefficients of negative moment for interior panels.*

east-and-west direction the adhesion would probably be less effective, but due to the flow of concrete into the cells of the tiles there is an interlocking which should assist in transferring tensile stresses into the tiles.

A similar relation between positive moments in the two directions is shown in Table 13, but the excess of the moments in the north-and-south direction over those in the east-and-west direction is only about 10 per cent, and the number of cases for which comparisons can be made is smaller than for positions of negative moment. The difference in depth to the center of the reinforcement for the two directions as shown in Table 10 and the distribution of loads (see Fig. 19) were such as to make an excess of stress

in the north-and-south direction appear reasonable. Furthermore, even if the stresses were the same in the two directions the greater moment arm for the north-and-south direction would be sufficient to account for the difference in moments.

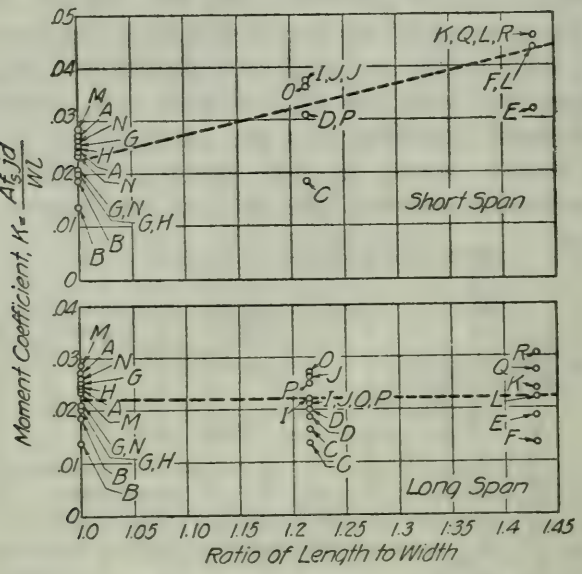


FIG. 34.—*Coefficients of negative moment for exterior panels.*

12. POSITIVE MOMENTS IN SLAB.

The stresses in the positive reinforcement, which formed the basis for computing the coefficients of positive bending moment, were developed by loading typical panels until the under surfaces of those panels were cracked to some extent and the stress in the reinforcement was generally beyond 30,000 lbs./in.^{2}

TABLE 12.—Ratios of Negative Moments in Exterior Panels to Negative Moments in Interior Panels.

Size of panel between girders.	Ratio of length to width.	Clear span.	Ratios of moments, exterior to interior.
Feet.		Feet.	
15 by 15	1.0	15	1.22
15 by 18.25	1.22	15	1.19
15 by 21.5	1.43	15	1.09
15 by 21.5	1.43	21.5	1.27
Average			1.19

TABLE 13.—Weighted Maximum Stresses in Slab Reinforcement and Resulting Coefficients of Positive Moment.

SQUARE PANELS.

Panel.	Applied live load.	Gage lines considered.	Weighted maximum stresses.[1]	Moment coefficients computed from, weighted maximum stresses.	
				Interior panel.	Exterior panel.
	Lbs./ft.²		Lbs./in.²		
A	615	1– 6	33,000	.....	0.0108
		7–12	30,000	.....	.0109
H	730	1– 6	30,000	0.0084	.....
		7–12	33,000	.0102	.....
M	545	1– 6	32,000	.....	.0117
		7–12	32,000	.....	.0130
Average	.....	.....	.....	.0093	.0116

INTERMEDIATE PANELS—SHORT SPAN.

I	605	7–14	39,000	0.0154	.....
P	525	7–14	39,000	.....	0.0176

INTERMEDIATE PANELS—LONG SPAN.

I	605	1–6	16,500	0.0046	.....
P	525	1–6	38,000	.0119	.....
Average	.....	.....	.....	.0083	.....

LONG PANELS—SHORT SPAN.

F	370	7–15	40,000	.....	0.0241
K	505	7–15	44,000	0.0200	.....
R	260	7–15	33,000	.....	.0269
Average	.....	.....	.....	.0200	.0255

LONG PANELS—LONG SPAN.

F	370	1–6	22,000	.....	0.0080
K	505	1–6	16,000	0.0045	.....
R	260	1–6	24,000	.....	.0118
Average	.....	.....	.....	.0045	.0099

[1] Stresses shown are from those observed on Apr. 22, 1920. See Fig. 19 and Table 4 for loads.

For the loads of April 22 on the typical panels, the adjacent panels were partially, and in some cases almost entirely, unloaded. This loading was used in the effort to produce the highest practicable positive moment.

Table 13 gives the coefficients of positive moment as computed from the weighted maximum stresses in the reinforcement at the centers of the spans. In Figure 35 these values of K are plotted as ordinates and the ratios of length to width of panel as abscissas.

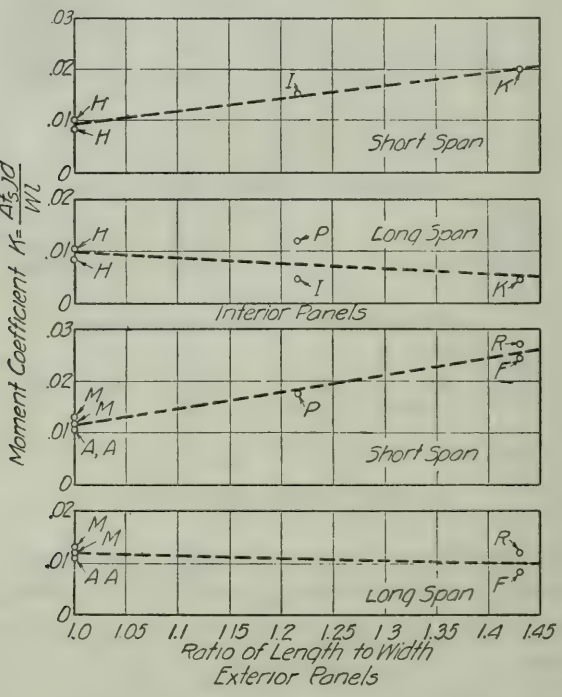


FIG. 35.—*Coefficients of positive moment for interior and exterior panels.*

The average coefficients of positive moment for exterior panels were in all cases greater than the corresponding coefficients for interior panels. The ratios of the average positive moments for exterior panels to the average positive moments for interior panels of the same size are given in Table 14.

A comparison of Table 12 with Table 14 shows that the excess of the moment for the exterior panels over that for the interior panels was slightly greater for positive moment than for negative moment one panel-length away from the wall.

The average coefficient of the positive bending moment for all panels with load as shown in Figure 19 is given in Table 16 as 50 per

cent of the average coefficient of negative bending moment for all panels with the uniform loads shown in Figure 18.

In Section II, 3, of this paper it was stated that the purpose of the arrangement of the load of April 22, 1920, was to increase the positive moments with as little increase as possible in the negative moments. In spite of the effort to avoid increasing the negative moments the stress in the negative reinforcement passed the yield point in a number of places before the loading of April 22 was completed. The manner of distribution of the final load and the reaching of the yield point in positions of negative moment are factors both of which would tend toward producing a high positive moment in relation to negative moment. For these reasons it seems that the values given represent as high ratios of positive to negative moment as could be obtained under any practical conditions.

13. MOMENTS IN CANTILEVERS.

Without the cantilevers shown in Figure 3 there would have been no section of negative moment at a greater distance in the

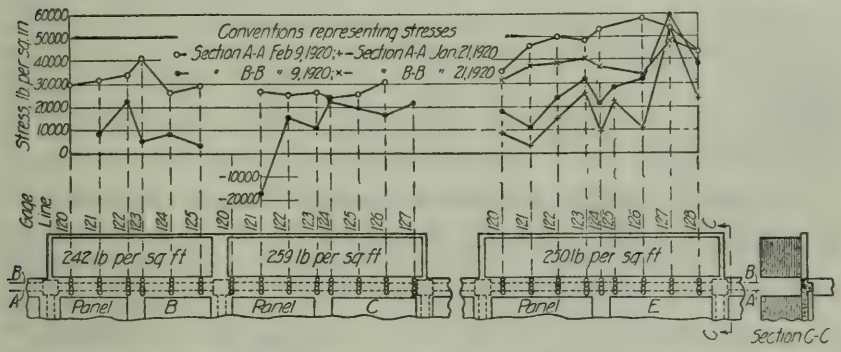


FIG. 36.—*Stresses in reinforcement in cantilevers and in slab opposite cantilevers.*

direction of the short span from the edge of the slab than one span length. Most building regulations provide that moments at such sections be taken somewhat greater than those for interior panels. With the cantilevers added the sections between panels *B* and *H*, *C* and *I*, and *E* and *K*, respectively, were further removed from the influence of wall panels. It was to give information on this feature that the cantilevers were added.

As shown in Figure 36, the stresses in the reinforcement of the cantilevers at section *B–B* were considerably greater than the stresses in the slab at section *A–A* for all three panels *B*, *C*, and *E*. This is somewhat unexpected in view of the indications, stated

TABLE 14.—Ratios of Maximum Positive Moment in Exterior Panels to Maximum Positive Moment in Interior Panels.

[Ratios are obtained from average coefficients given in Table 13 and apply to load of Apr. 22, 1920. See Fig. 19 and Table 4 for loads.]

Size of panel between girders.	Ratio of length to width.	Span.	Ratio of moments, exterior to interior.
Feet.		Feet.	
15 by 15	1.00	15	1.26
15 by 18.25	1.22	15	1.14
15 by 21.5	1.43	15	1.28
15 by 21.5	1.43	21.5	[1] 2.24
Average			1.23

[1] Not included in average.

TABLE 15.—Summary of Average Moment Coefficients.

[Values given are averages taken from Tables 13 and 14. Negative moment is for maximum uniform load; positive moment is for load of Apr. 22, 1920.]

Size of panel.	Ratio of length to width.	Span.	Moment coefficients.			
			Negative.		Positive.	
			Interior panel.	Exterior panel.	Interior panel.	Exterior panel.
Feet.		Feet.				
15 by 15	1.0	15	0.0186	0.0227	0.0093	0.0116
15 by 18.25	1.22	15	.0277	.0330	.0154	.0176
15 by 18.25	1.22	18.25	.0213	.....	.0083	.....
15 by 21.5	1.43	15	.0398	.0434	.0200	.0255
15 by 21.5	1.43	21.5	.0179	.0227	.0045	.0099

TABLE 16.—Comparison of Positive Moments with Negative Moments.

[Negative moment is for maximum uniform load. Positive moment is for load of Apr. 22, 1920. See Figs. 18 and 19.]

Size of panel between girders.	Ratio of length to width.	Span.	Ratio of positive moment to negative moment.	
			Interior panel.	Exterior panel.
Feet.		Feet.		
15 by 15	1.0	15	0.50	0.51
15 by 18.25	1.22	15	.56	.54
15 by 18.25	1.22	18.25	.39	.....
15 by 21.5	1.43	15	.50	.59
15 by 21.5	1.43	21.5	[1] .25	.44
Average			.49	.52

[1] Not included in average.

elsewhere, that the girders resisted very little moment by torsion, and the reason for the discrepancy is not apparent. The bending moments in pound-feet per foot of width at section *B–B* under the live load shown in Figure 36 plus the weight of the slab (50 lbs./ft.^{2}) were 2,900 at panel *B*, 3,070 at panel *C*, and 2,980 at panel *E*. The loads given in Figure 36 are based upon the areas loaded. If the moments at the two sections be assumed to be proportional to the observed stresses at the sections, it is found by multiplying the moments above stated by the ratios of stresses at section *A–A* to stresses at *B–B* that the moments at section *A–A* were 910, 1,590, and 1,570 lb.-ft. per foot of width at panels *B*, *C*, and *E*, respectively. Stating these moments in terms of the live and dead load w per square foot and the clear short span the moments found on section *A–A* at the edges of panels *B*, *C*, and *E* are $0.0098wl^2$, $0.023wl^2$, and $0.0267wl^2$, respectively.

These values afford an independent and fairly satisfactory check on the values given in Figure 32 for the same positions. The difference between stresses on sections *A–A* and *B–B* rather unsettles, however, the question of torsional resistance of the girders. The cantilevers do not seem to have a distinguishable effect on the moments one span length away from the cantilever support.

At section *B–B* the moments of the stresses observed in the reinforcement were approximately 0.53, 0.48, and 0.69 of the moment of the cantilever loads opposite panels *B*, *C*, and *E*, respectively, about the same section. These ratios are based on stresses observed on January 21, 1920, at panel *E* and February 9 at panels *B* and *C*, which was shortly after the load had been placed on the cantilevers. By February 9 the stresses in the cantilever at panel *E* had increased so that the moment of the stresses in the reinforcement was 0.86 of the external bending moment. For cantilevers *B* and *C* deformations were not measured after the load had been in place longer than about a week.

14. MOMENTS IN GIRDERS.

The beams were designed on the assumption that the load from an area bounded by intersecting lines drawn from the corners of the panels at 45° with the sides of the panels would be carried by the girders which extend across the ends of the panel. The load on the remaining trapezoidal area of each panel was assumed to be equally divided between the girders on the sides of the panel.

Measurements of deformations in the reinforcement of the girders were taken at various stages of the test in the effort to determine as to whether this method of design is approximately correct or whether the somewhat smaller moment coefficients which apply for uniform load could be used instead. The stresses observed were quite erratic and therefore seemed less reliable than those in the reinforcement of the slab.

For the maximum uniform load shown in Figure 13 the moment coefficients for the girders computed from the observed stresses averaged much less than the coefficients determined analytically from the trapezoidal load distribution assumed, but on account of the erratic distribution of the stresses the correctness of the coefficients determined from them is subject to question. The higher load of April 22 (see Figs. 14 and 19) gave higher coefficients just as has been found in many other tests.[9] Even in this case, assuming that the girders were fixed, the coefficients were lower than those given by analysis for trapezoidal and triangular distribution of load on the girders, but somewhat larger than the coefficients which would be obtained with the load distributed uniformly over the length of the girder. The stresses in the girders under the load of April 22, 1920, were observed in only a few places, and it does not seem safe to base important conclusions on these computed coefficients, especially in view of the erratic nature of the stress distribution under the maximum uniform load.

Under the intensified loading of November, 1920, in panels *H*, *J*, and *K*, with other panels partly loaded it seemed quite clear from the opening of a crack at the center of girder *JK*, that the yield point of the positive reinforcement in that beam had been reached. From the nature of the stress-strain curve for the reinforcement given in Figure 1, it is clear also that with the deflections as small as they were the stress can not have been much greater than the yield point. The sectional area of the positive reinforcement was 2.59 square inches. Assuming that the stress was at the yield point, 46,300 lbs./in.^{2}, and using the depth *d* of 16 inches to the reinforcement, as given in Figure 3, and assuming that the load on girder *JK* was the total live and dead load, *W*, of 124,000 pounds within the area inclosed by four 45° lines drawn from the ends of girder *JK* the resisting moment is found to be 0.0714 *Wl*. This is somewhat greater than the

[9] Westergaard and Slater, "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, p. 471; 1921.

maximum positive moment (0.0625 *Wl*) in a fixed beam under a triangular distribution of load but much less than the maximum moment (0.1667 *Wl*) in a simple beam similarly loaded. The conditions of restraint are unknown, but the beam under the loads shown in the frontispiece and Figure 16 would seem to be more nearly like a simple beam than a fixed beam.

15. ANCHORAGE REQUIRED FOR NEGATIVE REINFORCEMENT.

In order to prevent slipping of the negative reinforcing bars, hooks were furnished at the ends of the bars. If in such a case

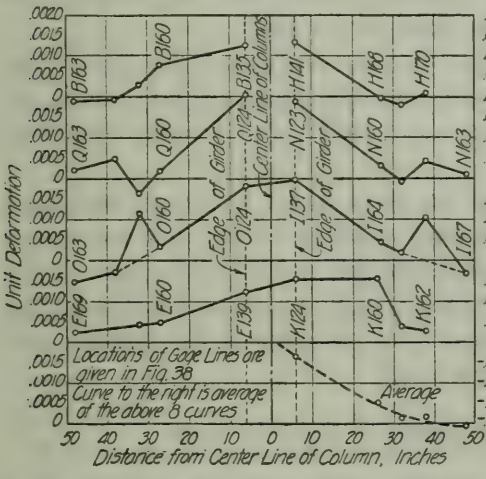


FIG. 37a.—*Points of zero stress for negative reinforcement in direction of short span.*

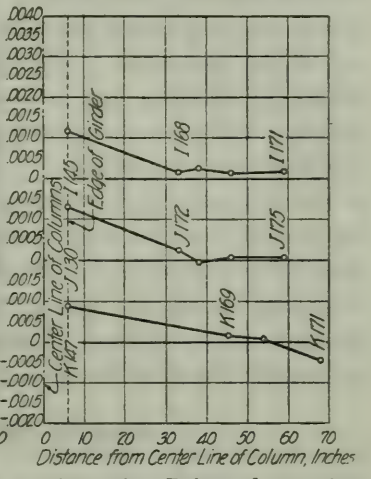


FIG. 37b.—*Points of zero stress for negative reinforcement in direction of long span.*

the tensile stress is reduced to zero before reaching the end of the bar, at the same time that the stress in the negative reinforcement where it crosses the edge of the girder has reached the yield point, the hook is not needed. An effort to determine whether such anchorage was necessary was made by observing the stresses at several points along the negative reinforcing bars which lay on the center lines of the panels. The location of these gauge lines is shown in Figure 38.

In six of the eight bars included in Figure 37 (*a*) a point of zero stress was reached within the length over which readings were taken. These bars extend in the north-and-south direction of the slab. Except for a few points, which seem erratic, the position of zero stress was consistent for the bars shown. The average

curve shown in the lower right-hand portion of Figure 37 (*a*) indicates that the point of zero stress occurred about 38 inches from the center line of the girders, or 32 inches from the nearest edge of the girders. This distance from the edge of the girder is 0.177 times the clear span of the slab

In two of the three cases shown in Figure 37 (*b*) a point of zero stress was found within the distance over which measurements were taken. These bars extended in the direction of the longer span. For the long panel the point of zero stress was about 55 inches from the center of the girders, or 49 inches from the nearest edge of the girder. This distance from the edge of the girder is 0.190 times the clear span of the slab.

For the long span in the intermediate-size panels the results are somewhat erratic, but indicate that the point of zero stress lies within a distance not greater in proportion to the span than that found in the long panel.

The data on the position of the point of zero stress are somewhat scant, but it seems that with bars of the size used here and spans as great, or greater, a safe design would result if the sum of the bond and the anchorage provided is sufficient to reduce the tensile stress to zero within a distance from the edge of the girder equal to 0.20 of the clear span of the panel.

16. SHEARING STRESSES IN RIBS OF SLAB.

In the calculations of the shearing stresses in the ribs, use was made of the fact that the bending moments were found to be different in the two directions of the square panels. (See Sec. III, 2.)

It was assumed that the loads carried to the girders were proportional to the negative resisting moments. Using the average of the ratios of the negative moments in the north-and-south direction to those in the east-and-west direction as the basis for the determination, it was found that 56 per cent of the panel load was carried in the north-and-south direction and 44 per cent in the east-and-west direction of the square panels.

There is some uncertainty as to what section should be considered effective in resisting shearing stresses. The type of construction is such as to make the tile so nearly an integral part of the floor slab that it seems that it must participate in resisting any stresses which could be resisted by a monolithic concrete construction. The scoring of the tiles furnished a bond with the

concrete, the pouring of the concrete on four sides of the tiles secured the tiles in place, and the partial filling of the cells with concrete insured the effective transmission of compressive stresses through the tiles. These considerations would lead one to expect that the ribs of the tiles in direct contact with the concrete would constitute a portion of the section which is effective in resisting shearing stresses.

The entire load within the portion of the panel area which is bounded by lines drawn through the ends of the ribs parallel to the sides of the panels must have been resisted by vertical shear in the ribs made up of concrete and the tile walls. In panel *H* the sum of the live and dead loads from November 9, 1920, to the date of writing (October 1, 1921) has been 1,463 lbs./ft.^{2} Assuming that equal loads were carried by all parallel ribs and that, as stated in a preceding paragraph, only 44 per cent of the load was carried in the east-and-west direction, the maximum shearing stress developed on each of those ribs was 405 lbs./in.^{2} It is likely, however, that the ribs which extended along the center lines of the panels carried larger loads, and consequently greater shearing stresses, than those near the edges. On the other hand, it is possible that the increase in resisting section caused by the flowing of the concrete into the cells of the tiles was of appreciable effect in increasing the shearing resistance of the rib.

In the north-and-south direction there were tile walls which probably assisted the concrete ribs materially in resisting the shearing stresses. Assuming that the remainder of the load (56 per cent) was carried in the north-and-south direction, the maximum computed shearing stress in the composite rib (made up of the concrete and the two[10] tile walls in contact with it) was 375 lbs./in.^{2} There has been no sign of diagonal tension failure at that load. Assuming the entire shearing stress to have been resisted by the concrete without assistance from the tiles requires a shearing resistance of 500 lbs./in.^{2} in the concrete. Since tests have indicated that even with thorough end anchorage of the longitudinal reinforcement of beams which have no stirrups or bent-up bars, diagonal tension failure may generally be expected at shearing stresses not greater than 250 lbs./in.^{2} for concrete such as was used in this test, it seems obvious that the tile walls must have been of considerable assistance in resisting the shearing stresses.

[10] As the shells of the tiles were not much cracked it is possible that the middle rib also contributed appreciably to the shearing strength.

These conditions indicate that it is proper and safe to consider that the tile walls which are in contact with the concrete rib are capable of carrying a shearing stress which is not less per square inch of tile than the shearing strength per square inch of the concrete rib.

In view of the high shearing stress developed without failure in the ribs which had no tile walls in contact with them, a somewhat greater allowance for the shearing resistance of the concrete in those ribs than is generally recognized for concrete beams which have no web reinforcement would probably be justified.

If it be assumed that the loads carried in the two directions were equal and that the apparent difference in moments was due to tensile stresses in tiles and concrete, the shearing resistance would be about 325 lbs./in.^{2} in the ribs of concrete and tile in the north-and-south direction and 460 lbs./in.^{2} in the concrete ribs in the east-and-west direction, but the conclusions would not be far different from those already stated.

17. SHEARING STRESSES IN GIRDERS.

Assuming that only 44 per cent of the load in panel *H* was transmitted in the east-and-west direction, the load applied to girder *HI* (between panels *H* and *I*) in the loading of November, 1920, was 72,600 pounds. Adding 30,000 pounds assumed to be applied to girder *HI* by panel *I*, the total load on girder *HI* is found to be 103,000 pounds. The girder *HI* was 12 inches in width and 15⅛ inches in depth from the center of the top reinforcement to the bottom of the girder. The end of the girder was reinforced with U-shaped stirrups made from ⅜ inch round bars and spaced 3 inches apart in a horizontal direction. The stirrups were anchored at their ends and were inclined so that they made an angle of about 60° with the horizontal.

The computed shearing stress based upon the load of 103,000 pounds is 342 lbs./in.^{2} The computed tensile stress in the stirrups, using the formula $P = \frac{2}{3}\frac{Va}{jd}$, is 32,800 lbs./in.^{2} where P is the total load carried by the stirrup and a is the distance between stirrups at right angles to their direction. Diagonal tension cracks appeared in the girder at the highest load, but these were not large.

Assuming the load on girder *JK* to be 124,000 pounds as indicated in Section III, 14, the shearing stress which that girder

has had to carry for over a year[11] is 467 lbs./in.^{2} The tensile stress in the stirrups computed by the formula $P = \frac{2}{3}\frac{Va}{jd}$ is 37,000 lbs./in.^{2} The web reinforcement was the same as for girder *HI*.

It is not known accurately how great was the maximum load carried by the girders on the long sides of the oblong panels. However, any reasonable assumption as to the amount of load carried by these girders gives a shearing stress which is considerably smaller than that computed for girder *HI*.

18. CRACKS.

Careful examination for cracks in the bottom of the slab was made at each of three stages of the test: (*a*) About February 10,

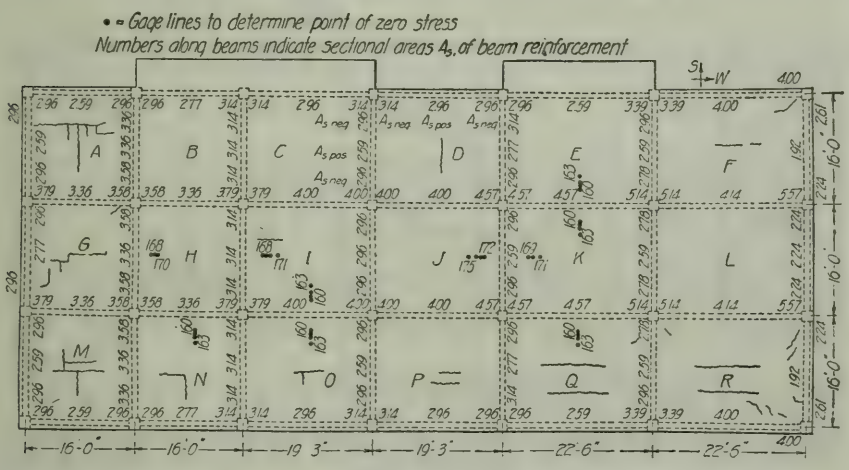


FIG. 38.—*Plan of slab showing cracks in under surface with maximum uniform load in place 2 to 21 days; also sectional areas of beam reinforcement.*

1920, after the maximum uniform load had been in place about two weeks; (*b*) April 2, after the maximum uniform load had remained in place about nine weeks; and (*c*) April 22, after the load on certain panels had been increased in order to increase the positive moment. This last examination was made only in the panels in which the load had been increased. Figures 38 to 40 give the location of cracks which were found at these three stages. The intensities of the load on various portions of the slab may be found in Table 4.

The presence of loading material on the top of the slab interfered with a thorough examination of the top surface. For this reason no crack diagrams for the upper surface are given. After the maximum uniform load had been in place about two weeks

[11] See footnote 5, p. 739.

the stress in the positive reinforcement was still very low and correspondingly few cracks had developed. The largest crack was less than 0.005 inch wide. There were more cracks in the corner panels *A*, *M*, and *R* than in any other panels, and correspondingly the measured stresses in the positive reinforcement were greater for these panels than for the other panels.

After the maximum uniform load had remained in place about nine weeks the number and size of the cracks had increased considerably. This increase was especially marked in the square panels and in the two long corner panels. The largest cracks at this time were less than 0.01 inch wide. However, in panels *E* and *L* no cracks could be found and in several other panels very

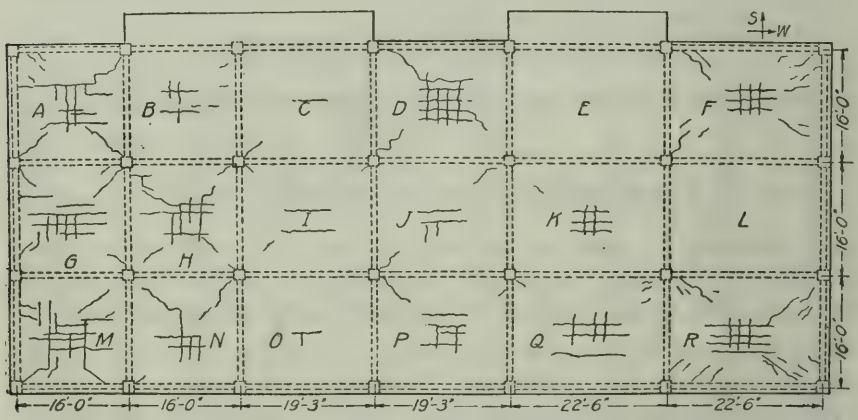


FIG. 39.—*Plan of slab showing cracks in under surface with maximum uniform load in place 55 to 73 days.*

few cracks were present. In general, the diagonal cracks occupied the corners of the panels. Cracks parallel to the panel edges occupied the central portions of the panels and usually followed along the edges of the tiles. For this reason they were somewhat difficult to detect and probably more cracks of this type were present than are shown. The regularity of the formation of the cracks in certain panels (see panels *D*, *F*, and *R* in Fig. 39) was sufficient to give the location and outline of the tiles over a considerable area. The diagonal cracks generally crossed the tiles, but in a few cases they followed the edges of the tiles in a zigzag fashion.

When the load on certain panels was increased—that is, under the loading of April 22, 1920—the diagonal cracks extended farther toward the centers of the panels and increased considerably in size. The cracks parallel to the sides of the tiles increased in size

but apparently not so much in extent as the diagonal cracks. The largest diagonal crack was 0.020 inch wide and was found in panel *A*. The largest crack parallel to the edges of the panel was 0.025 inch wide and was found in panel *K*. All other cracks in the under surface of the slab were less than 0.01 inch wide at this stage of the test. (See Fig. 40.) While it was evident that the cracks

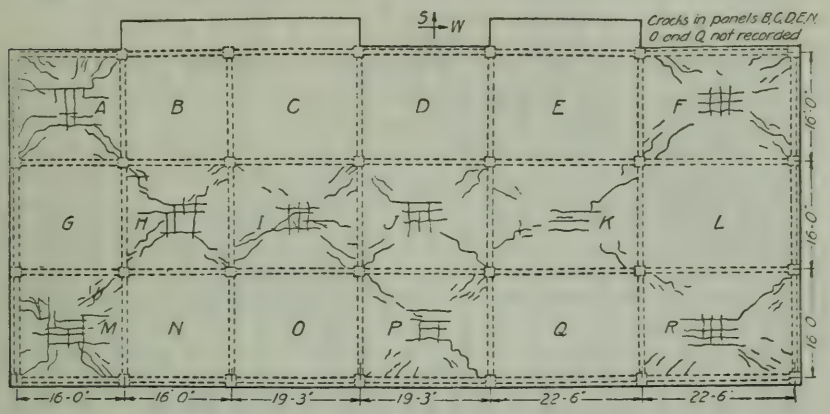


FIG. 40.—*Plan of slab showing cracks in under surface with load of April 22 in place.*

had opened slightly between the April and the November tests they were still generally quite small and no new cracks were found.

19. FACTOR OF SAFETY.

Many tests which have been made on slabs of buildings in service have been subjected to the criticism that because the test was not carried to the point of failure of the slab it did not furnish information as to the factor of safety of the structure, although at the loads applied the observed stresses were small. Important significance is given to this criticism by the fact that a simple beam having a small amount (say, 0.5 per cent) of reinforcement of structural grade steel may be expected to fail at a load about 30 per cent greater than the load which develops a measured stress of 16,000 lbs./in.^{2} in the reinforcement.[12]

Further criticisms of building tests have been made on the ground that since only a small portion of the floor area was loaded, the loaded portion is materially assisted by the unloaded portion adjacent to it, and that in the tests the load is not left on the floor long enough to show the full extent of its effect on the slab.

[12] Westergaard and Slater, "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, Figs. 31–34, p. 478–481; 1921.

In planning the test described in the foregoing pages, pains were taken to make the conditions so severe that any weakness suggested by the criticisms referred to would be fully exposed.

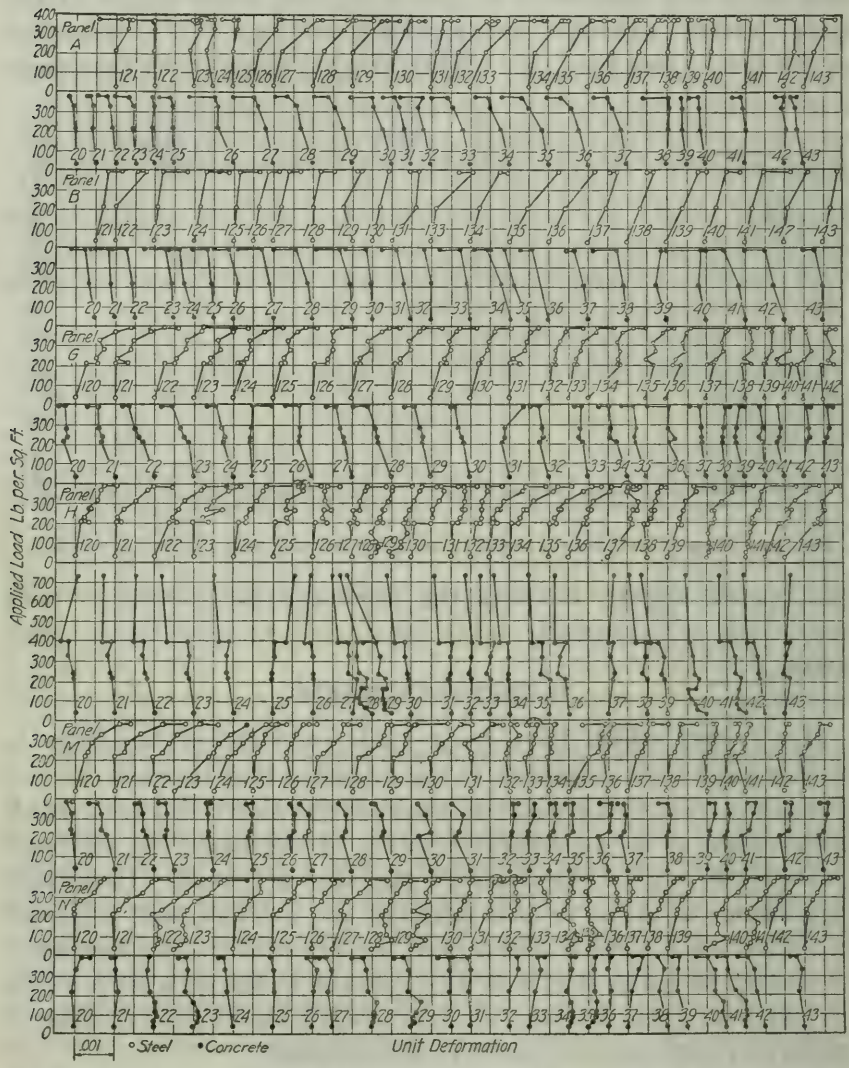


FIG. 41.—*Load-deformation curves for steel and concrete for positions of negative moment in square panels.*

An effort was made to test the slab to failure with all panels loaded so as to determine the factor of safety for the panels of the various sizes.

Under the maximum uniform loading shown in Figure 18 the ratios of the live and dead loads to the "design loads" of Section

II, 2, were 5.4, 4.9, and 5.8 for the square, intermediate, and long panels, respectively. It seemed that continuing to increase the load uniformly would make the conditions for negative moment so severe before high stresses due to positive moment were developed that dependable information on the ratio of positive to negative moment would not be obtained. This consideration together with the difficulty and expense of providing additional

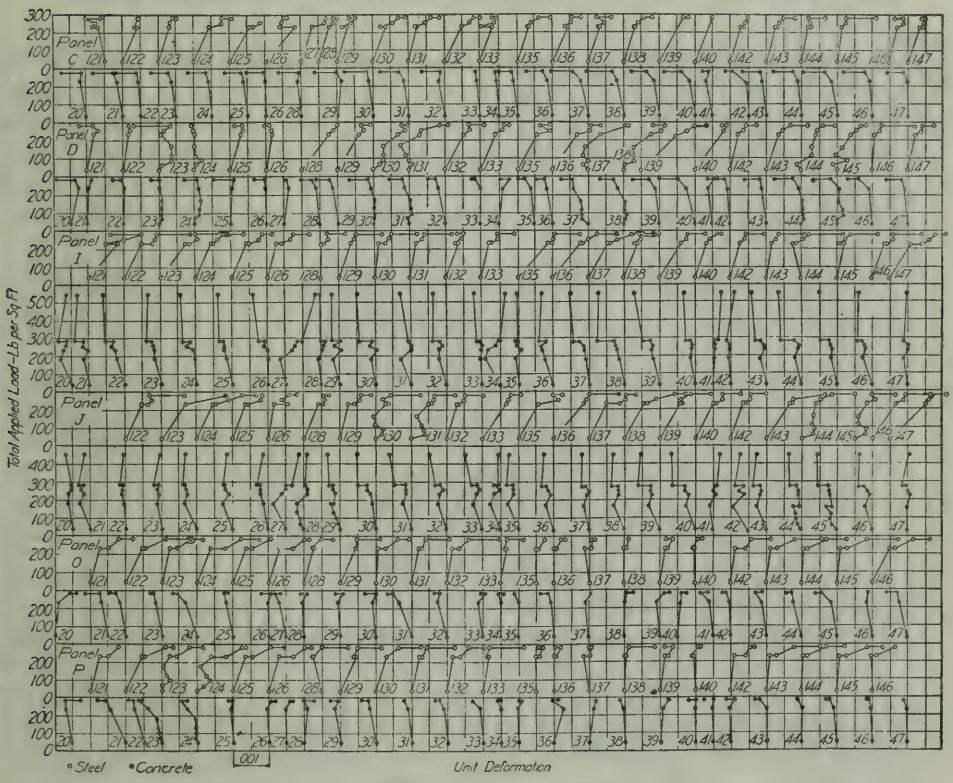


FIG. 42.—*Load-deformation curves for steel and concrete for positions of negative moment in intermediate panels.*

loading material led to the redistribution of load shown in Figure 19. While it is believed that the factor of safety should be based upon a load uniformly distributed over all panels of the same size (since the design is based upon such a distribution and since such a loading would probably be the most severe) such a loading was not carried far enough to show what the factor of safety was. It is necessary, therefore, to make the best possible use of the information available.

The condition of the slab after the load shown in Figure 19 had been in position six months was such as to indicate that loads of the maximum intensity there shown for each panel size could have been applied simultaneously over all the panels of that size without causing failure. This belief seems abundantly confirmed by the results of the test of November, 1920.

While bearing in mind the qualifications here named it seems safe to assume that the factors of safety for the interior panels

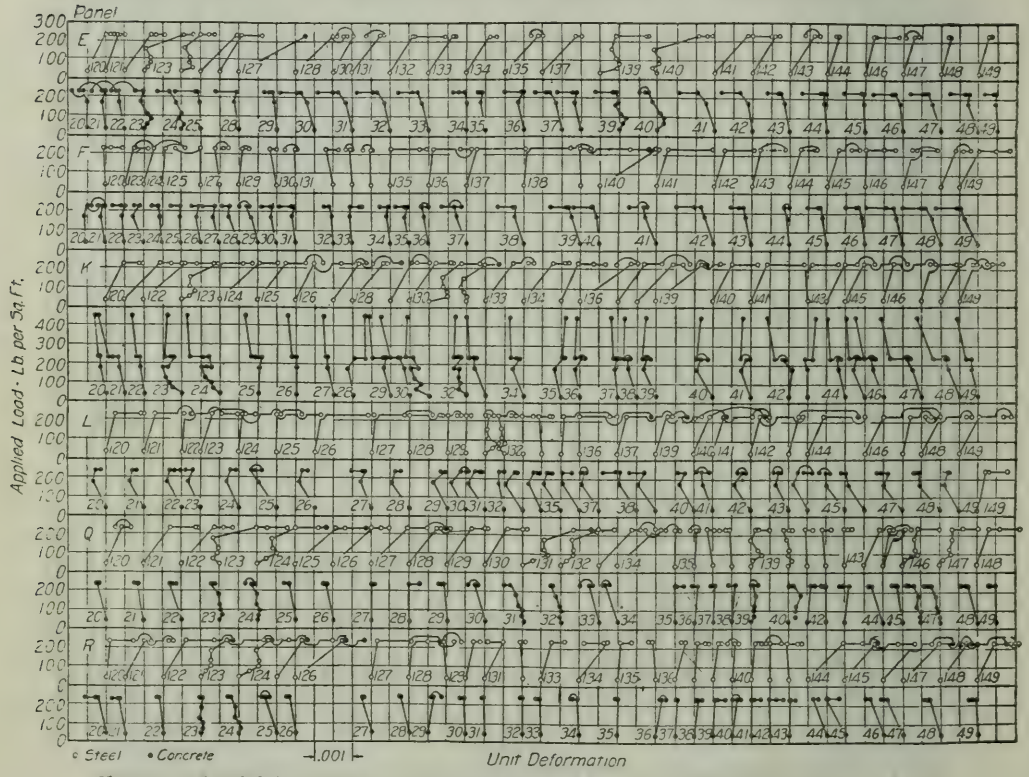


FIG. 43.—*Load-deformation curves for steel and concrete for positions of negative moment in long panels.*

of this test slab were not less than the ratios of the loads which were in place from April to November, 1920 (see Fig. 19), to the design loads stated in Section II, 2. These ratios are 8.7, 9.0, and 10.6 for the square, intermediate, and long panels, respectively.

Attention has been called to the fact that panel *F* settled down upon the shores between April and November, 1920. After the shores were removed a period of 30 hours elapsed before any load was removed. During that time the deflections increased 0.04

inch. It is obvious that the extension of the ratios above given to the case of a corner panel has not been justified.

The loads which have been in place from November 9 to the present date (October 1, 1921) on certain panels give ratios of

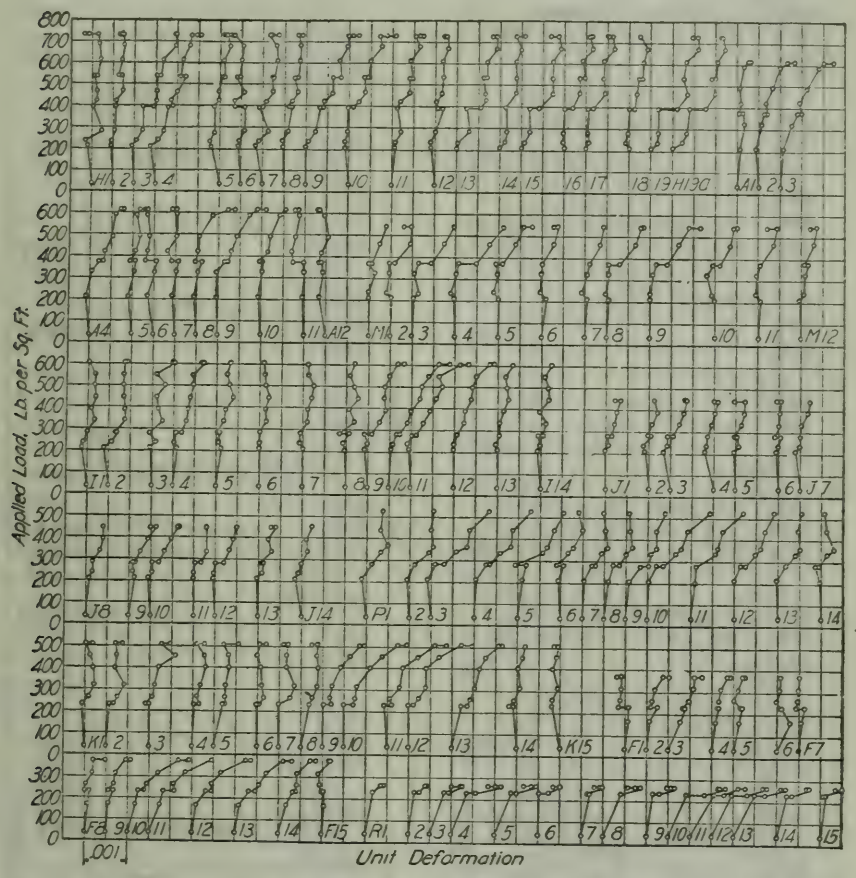


FIG. 44.—*Load-deformation curves for steel at positions of positive moment in panels H, A, M, I, J, P, K, F, and R.*

test loads to design loads, computed in the same way, of 16.2, 17.0, and 18.6 for the three sizes of panels.

In computing the above ratios the test load (sum of live and dead loads) was divided by the "design loads" given in Section II, 2. In order to place the ratios upon the basis of an equivalent uniform load the test loads used in computing these ratios were taken as 8 per cent less than those reported in this paper.

(Text continued on page 790.)

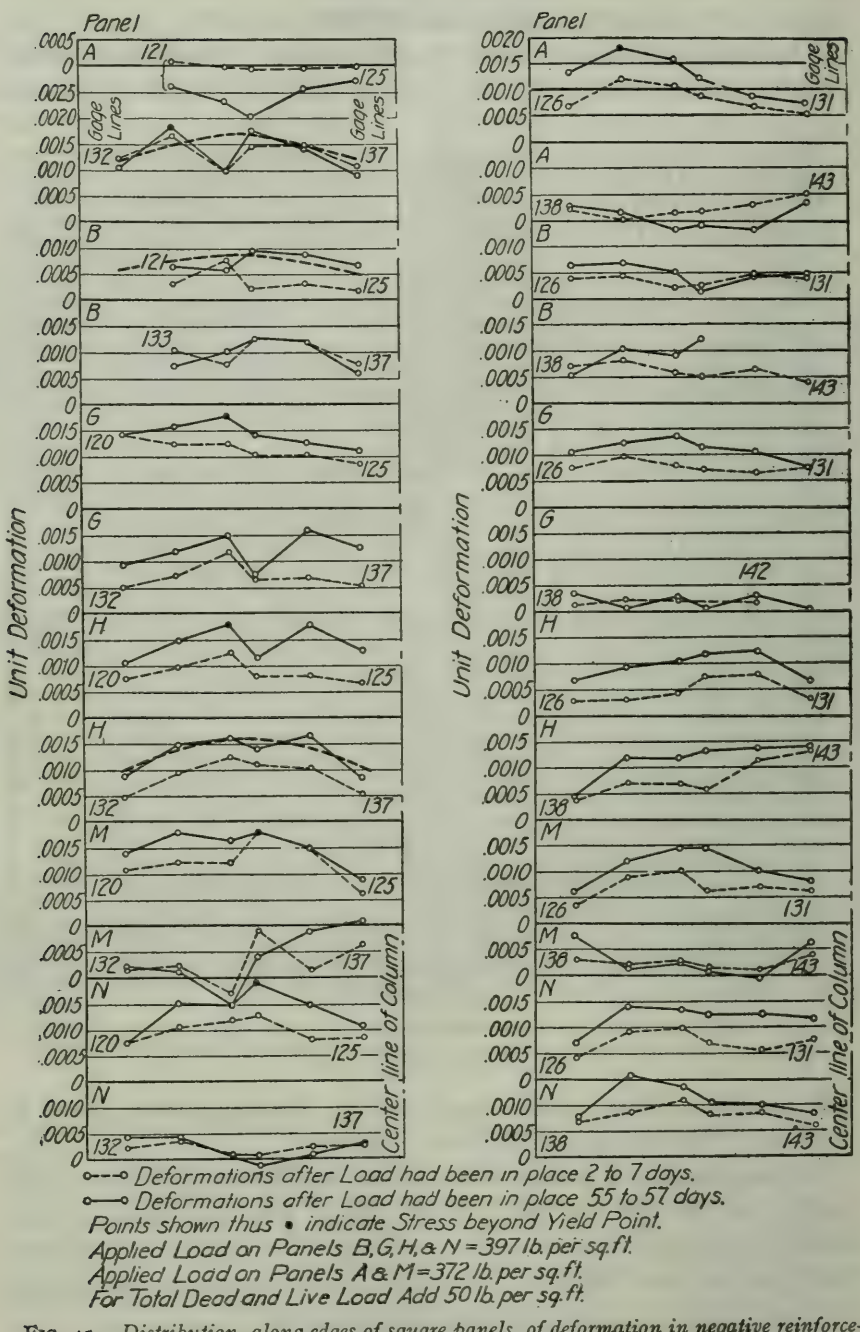


FIG. 45.—*Distribution, along edges of square panels, of deformation in negative reinforcement.*

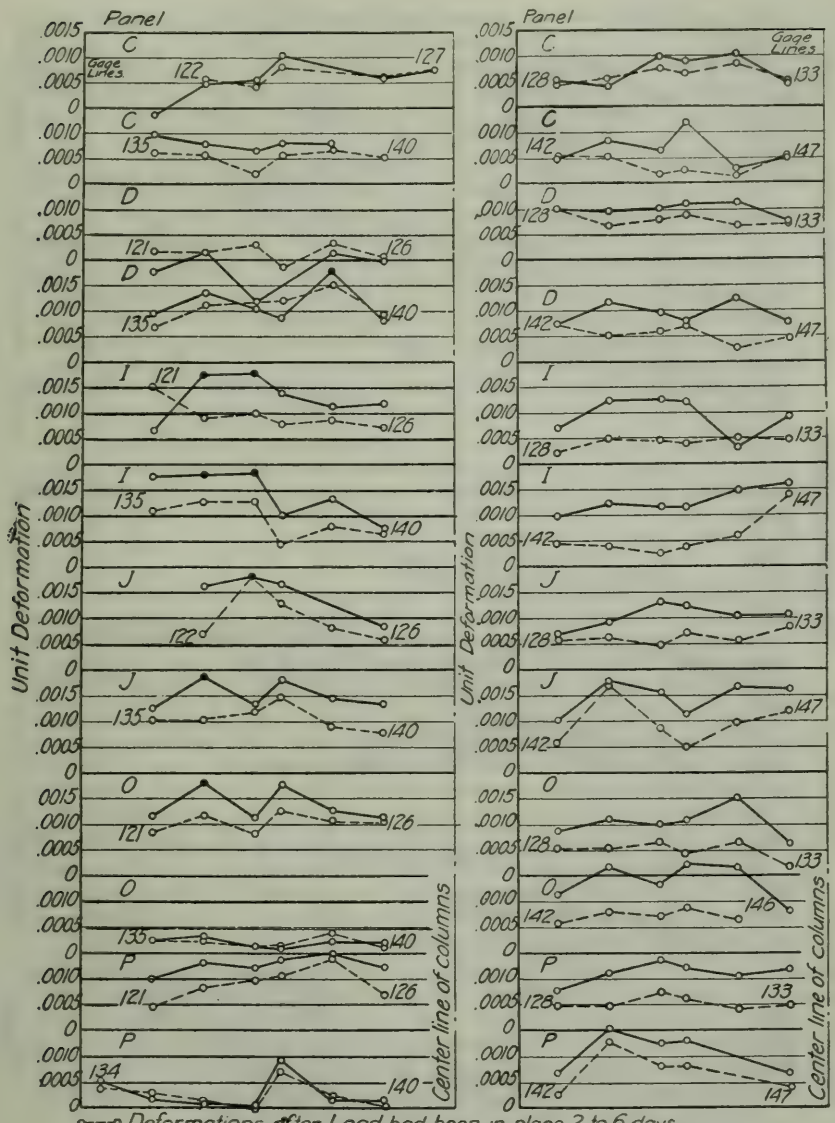
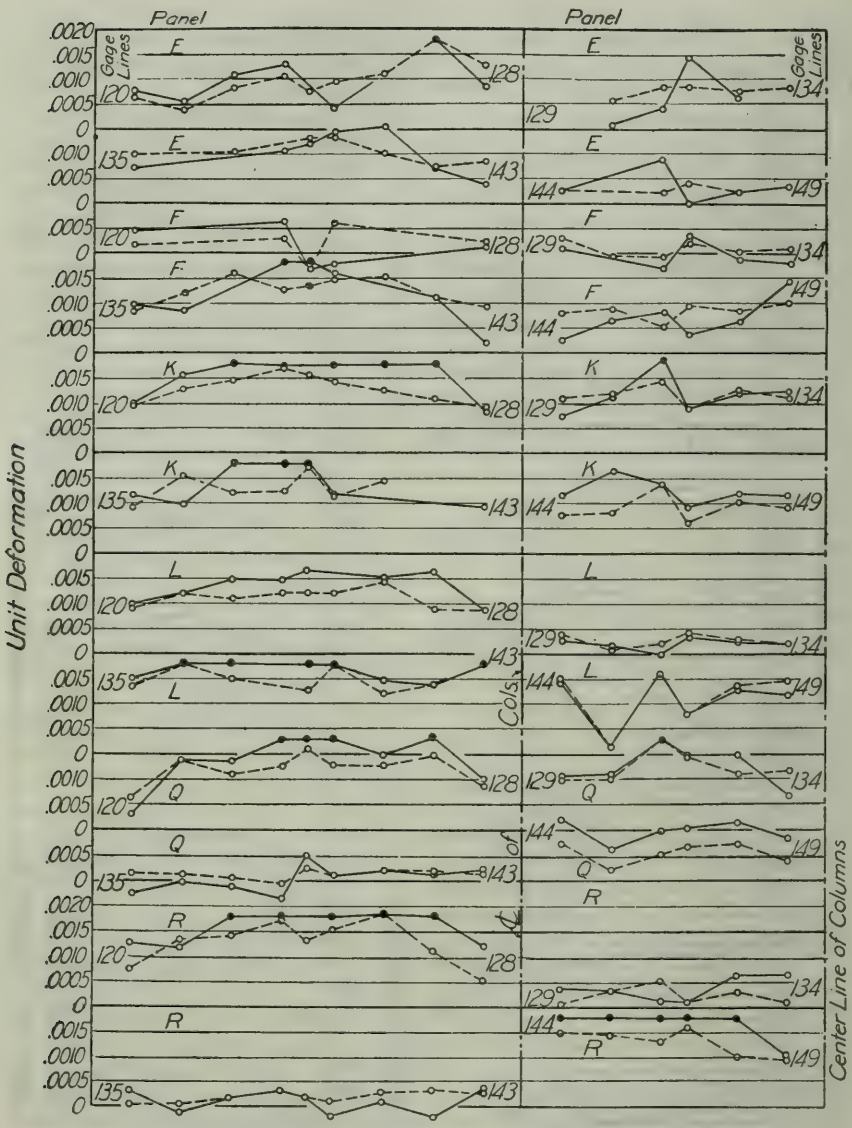


FIG. 46.—*Distribution, along edges of intermediate panels, of deformation in negative reinforcement.*



o---o Deformations after Load had been in place 17 to 21 days.
o—o Deformations after Load had been in place 71 to 73 days.
Points shown thus • indicate Stress beyond Yield Point.
Applied Load on Panels E, F, K, L, Q & R = 230 lb. per sq. ft
For Total Dead and Live Load Add 50 lb. per sq. ft

FIG. 47.—*Distribution, along edges of long panels, of deformation in negative reinforcement.*

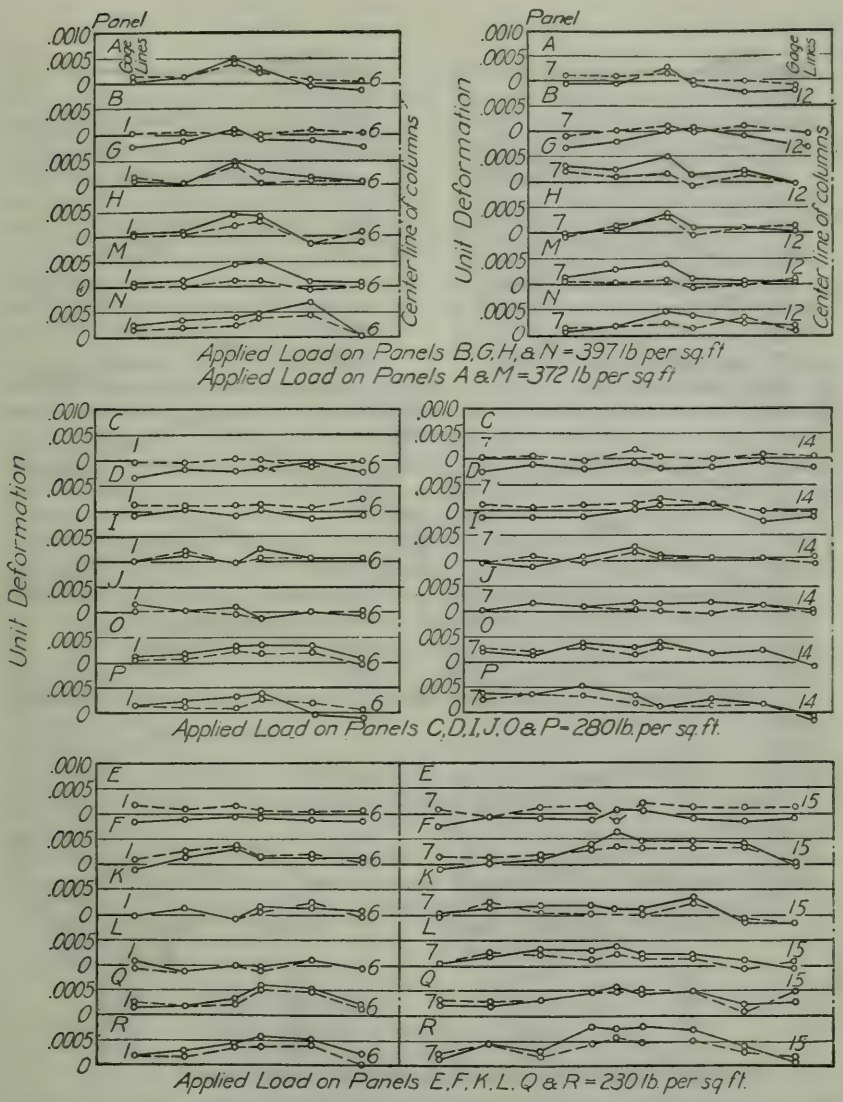


FIG. 48.—*Distribution, along center-lines of all panels, of deformations in positive reinforcement for maximum uniform load.*

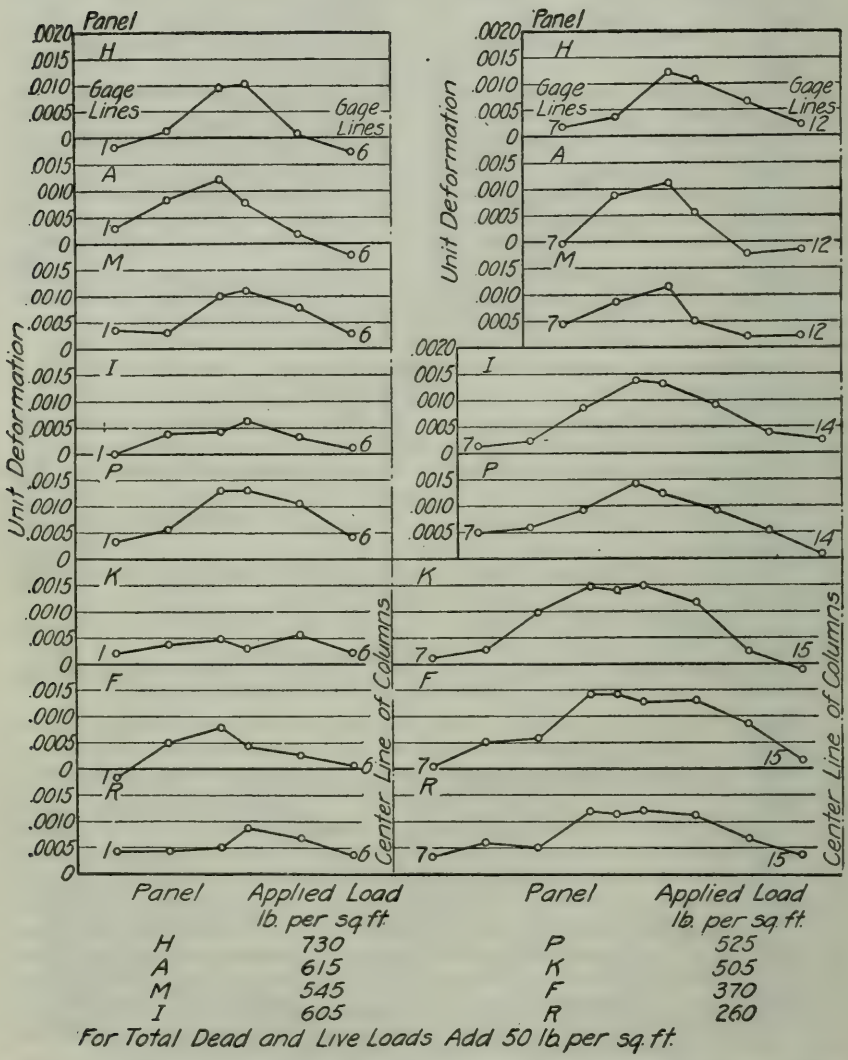


FIG. 49.—*Distribution, along center-lines of all panels, of deformation in positive reinforcement for load of April 22, 1920.*

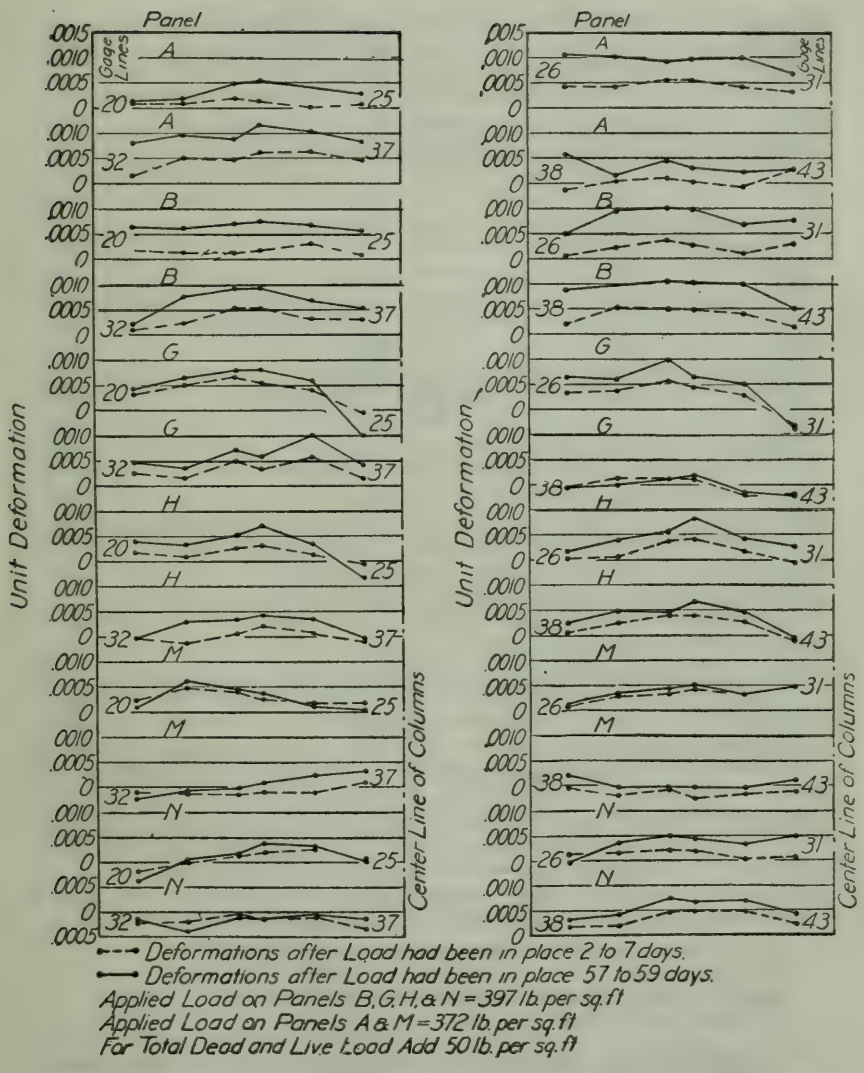


FIG. 50.—*Distribution of deformation in concrete along edges of square panels.*

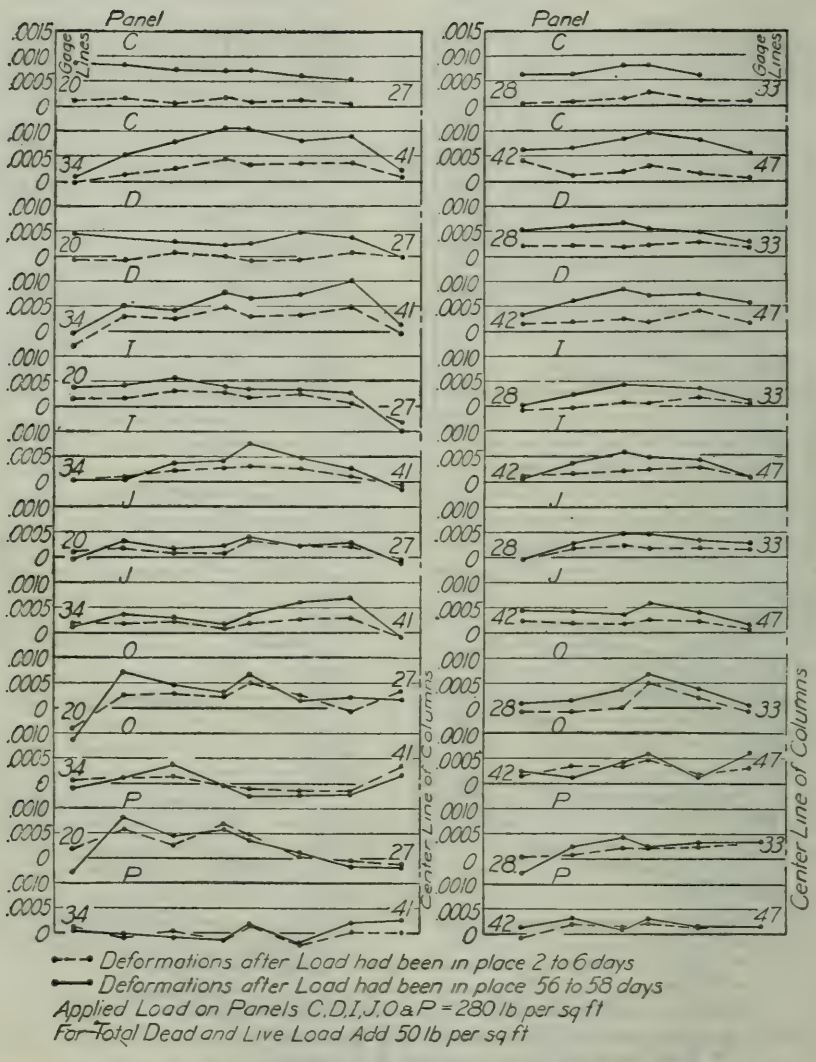


FIG. 51.—*Distribution of deformation in concrete along edges of intermediate panels.*

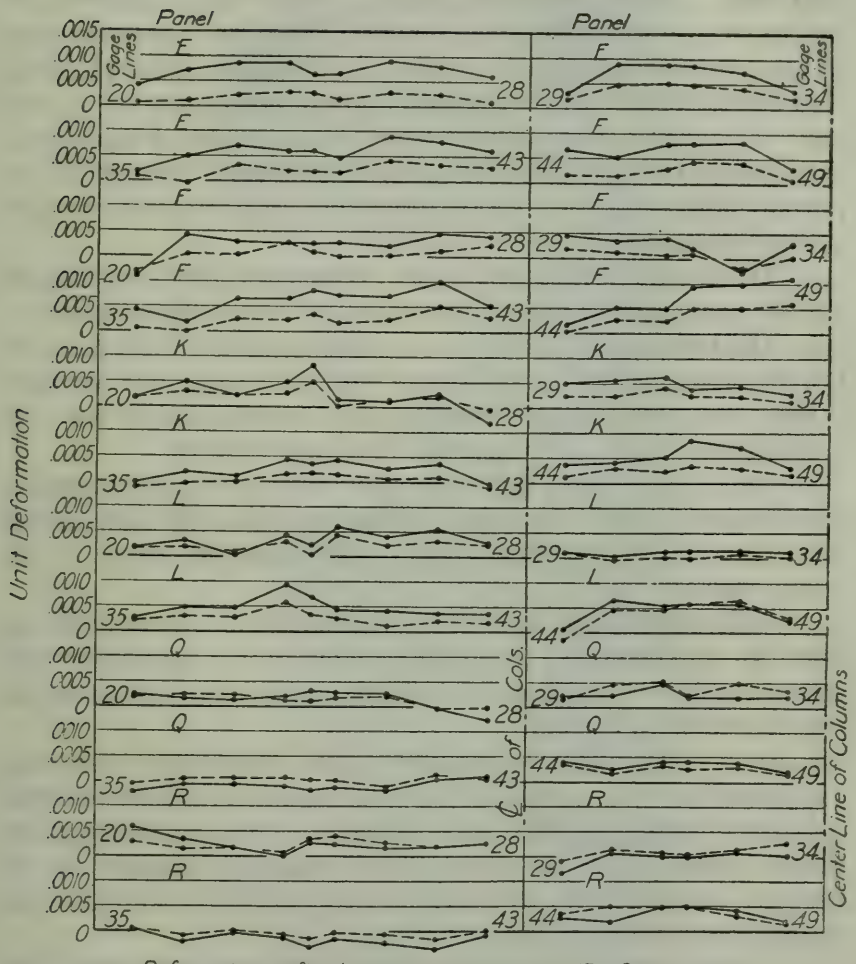


FIG. 52.—*Distribution of deformation in concrete along edges of long panels.*

20. GENERAL COMMENTS.

It has been the purpose of this test to furnish data which will afford a basis for the design of slabs of the type tested. The essential requirement of a floor structure is that it carry the design load with a proper factor of safety. There is no objection to making use of any additional strength afforded by other elements of the structure than those usually considered in design provided that these elements of strength can be depended upon to be present. To guard against the extension of the results of this test to cases where they may not be properly applicable because of important differences from the Waynesburg slab, attention is called to the following points:

1. The moments measured by the coefficients given in this paper are the moments of the measured stresses in the reinforcement.

2. The increase in stress with a constant load on the slab and the increase in moment coefficients with increasing load are indications that the tensile strength of the concrete and of the tiles assisted in reducing the stresses in the reinforcement.

3. Other tests have indicated that with low percentages of reinforcement only a portion (often less than one-half) of the total moment is accounted for by the observed stress in the reinforcement.

4. With larger percentages of reinforcement it is to be expected that the proportion of the total moment to be resisted by the stresses in the reinforcement would be larger than that found in this test to be so resisted.

5. Most of the negative moment found analytically has been accounted for [13] by assuming that the same ratio existed between moment of steel stress and total moment as was found in tests of simple beams. The moment of the observed stresses due to negative moment was between one-half and two-thirds of the moment found analytically.

6. A certain amount of dome or arch action within the structure may possibly have contributed to its carrying capacity. The likelihood of assistance from such a source probably will vary in some measure with the ratio of the span to the depth of the slab. Therefore, the moment coefficients found applicable to the structure tested should not be extended forthwith to structures having a larger ratio of span to slab thickness than that which existed in the slab tested.

[13] "Moments and stresses in slabs," Proc. Am. Concrete Inst., 17, Table XII, p. 498 and Fig. 33, p. 480; 1921.

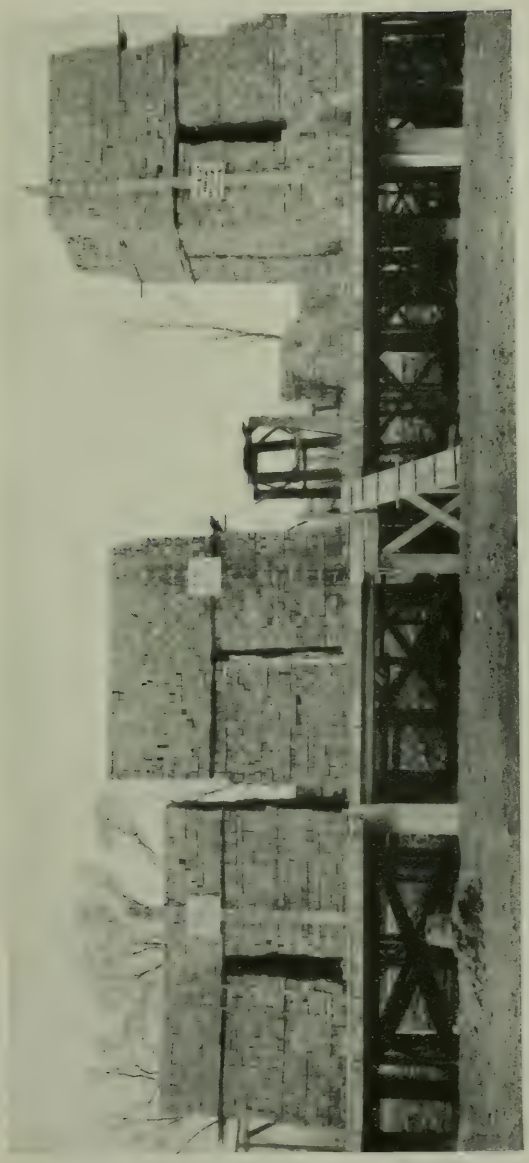


FIG. 53.—*Final load in place from November, 1920, to date (October 1, 1921); view from south.*

An analysis of a tied arch or dome, however, will generally indicate as much tension in the tie as though the load were carried by bending of a beam or slab of equal depth. It would seem, therefore, that dome action would constitute an additional source of strength for this slab only in case it were possible by this means to throw into the girders some of the tensile stresses which otherwise would have to be carried by the slab.

7. It is probable that with the loading of November, 1920, there was some arching of the load. It would be difficult in most cases to apply a load of intensity equal to that load without having an equal amount of arching, but if dependence is deliberately placed upon arching of the load, consideration must be given to such factors as the span of the slab, the character of the loading material, and the possible distribution of the load.

8. The high yield point of the slab reinforcement, 54,000 lbs./in.^{2}, permits more general cracking of the concrete within the elastic range of the slab's action than would have been possible with mild steel reinforcement. This is of advantage for studying the behavior of the slab under working loads, but the maximum load carried would, of course, be less with mild steel than with the hard-grade steel used.

9. In applying the results of this test to the formulation of standards for design proper consideration should be given to the possibility that in practice the workmanship may be inferior to that secured in the test slab. However, the concrete strengths and the depths to the reinforcing bars given in Tables 2 and 9 will indicate that the pains taken was not excessive.

In order that the tiles may be effective in resisting shearing stresses and compressive stresses, wherever this form of construction is used, it is obvious that a high degree of integrity between the tiles, the concrete, and the reinforcement is essential. This is emphasized by the probability previously indicated, that the resistance developed by the structure is, in part, accounted for by the tensile resistance of the concrete and tiles. This integrity can be secured only by having the concrete mixed wet enough and by having it worked into place sufficiently to insure proper filling of the concrete around the tiles and the reinforcement. At the same time the concrete should be dry enough that too large a quantity of it will not flow into the tiles. In order to avoid the loss of excessive quantities of concrete by flowing into the tiles there may be a temptation to mix the concrete so dry that the

securing of the required integrity will be difficult. The misplacement of tiles also is likely to occur, and when it does the strength of the construction may be affected. These considerations make it clear that careful attention must be given to all phases of the construction in order to insure good workmanship.

10. There is nothing in the type of construction described in this paper to distinguish its action sharply from that of a similarly reinforced solid concrete floor. It would seem desirable, however, before extending conclusions derived from this test to another form of construction that the other form of construction also be tested. This is especially true regarding features which are contrary to generally accepted practice.

In order to avoid danger of encouraging too great expectations from the type of construction described in this paper, specific attention has been called to all the features which, except for such caution, might foster overconfidence in the merits of such a structure. It seems proper, on the other hand, to call attention to the fact that the feature which finally should determine the merits of a given floor construction is its ability to carry load without objectionable distortion of the structure under long-continued service.

In order to avoid wrong conclusions on account of the fact that the strain gauge measurements do not show directly what are the total moments, special efforts were made to determine what load the slab would carry without failure.

Obviously in order to be finally conclusive on such questions as repeated loading, vibration effects, shock, shrinkage, expansion, contraction, etc., which may decrease the tensile resistance of the concrete and the tile, more extensive tests would be needed than those which have been made. The tests which have been made are probably, however, more extensive and more thorough than any that have ever before been made in the introduction of a special form of construction.

21. SUMMARY.

Deformations in the tiles were on the average 70 per cent as great as those in the adjacent concrete. The compressive unit stresses in the tiles probably were equal to, or greater than, those in the concrete.

The walls of the tile in contact with the concrete ribs seem to have been effective in resisting shearing stresses at least equally with the concrete. It is reasonable that this should be so.

The average negative moment as determined from the measured stresses for the interior square panels was $0.0186Wl$. That for the short span of the interior intermediate-size oblong panels was $0.0277Wl$ and the corresponding moment for the long panels was $0.0398Wl$. The average negative moment in the long span of the rectangular panels was $0.0213Wl$ for interior intermediate-size panels and $0.0179Wl$ for the interior long panels. In all the above cases l is the clear short span of 15 feet. The quantities given represent only the moment of the observed stresses in the reinforcement. The true stresses may have been 5 to 10 per cent greater than the observed stresses. The moment found analytically would probably be as much as 50 to 75 per cent greater than the values given.

The average negative bending moment for exterior panels was 20 per cent greater than that for interior panels of like size. This was for the reinforcement across the girder one span length from the wall. For interior panels the average positive moment under the concentrated loading of April 22, 1920, was 49 per cent of the average negative moment under the maximum uniform load. The average positive moment for exterior panels was 25 per cent greater than the positive moment for interior panels. The slabs on which this comparison is based had both positive and negative reinforcement extending into the wall girders.

The average distance of the point of zero stress in the negative reinforcement from the edges of the girders was less than one-fifth of the clear span.

For uniform live loads of 275 lbs./ft.^{2} on the square panels, 230 lbs./ft.^{2} on the intermediate panels, and 175 lbs./ft.^{2} on the long panels, the deflection at the center of the panels was about one nine-hundredth of the clear short span. These loads are about 3.5 times the "design loads" referred to in Section II, 2.

Ratios of live and dead load to the "design load" of Section II, 21, averaged approximately for all sizes of panel, 5.4 for the maximum uniform load, 9.4 for the loading of April 22, 1920, and 17.3 for the somewhat more concentrated loading of November, 1920, which has been on three panels of the slab for over a year.

WASHINGTON, March 31, 1922.

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[Part of Vol. 17]

MAGNETIC SUSCEPTIBILITY AND IRON CONTENT OF CAST RED BRASS

BY

L. H. MARSHALL, Research Associate

R. L. SANFORD, Physicist

Bureau of Standards

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BY

L. J. BRIGGS
and
H. M. DADOURIAN

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MAGNETIC SUSCEPTIBILITY AND IRON CONTENT OF CAST RED BRASS.

By L. H. Marshall [1] and R. L. Sanford.

ABSTRACT.

The presence of iron in commercial brass is often objectionable, particularly if it occurs as discrete, poorly alloyed particles. In order to obviate any such harmful effects, a very low ferrous content is frequently specified. Therefore, a rapid, nondestructive method for quantitatively determining its presence would be of great value in practice. A magnetic method of inspection would fulfill the requirements of such a test if a definite relationship exists between some magnetic property and the iron content of the metal.

With these facts in mind a study was made of the magnetic characteristics of a series of specially prepared samples of tin-red brass.[2] The composition of these specimens was quite uniform except for the intentional variation in iron content from about 0 to 0.75 per cent. Magnetic properties were determined in the cast condition and after annealing 15 minutes at 625° C., 8 hours at 800° C., and 16 hours at 800° C.

Microscopic examination indicated that less than 0.14 per cent iron went into solid solution in the matrix of the alloy, as this amount, or more, caused the appearance of an iron-rich constituent. These ferrous aggregates occurred as pale, rounded areas, which were apparently unaffected by the annealing treatments mentioned above. It was possible to estimate roughly the per cent of iron present from the number and size of these areas. The iron content had no noticeable effect on the grain size of the brass.

The results showed that (*a*) the magnetic properties are not a precise index of the iron content of the cast metal; (*b*) the magnetic susceptibility is markedly affected by changes in physical condition produced by heat treatment; (*c*) even after the material has been thoroughly annealed, there is still no simple relationship between the magnetic susceptibility and the iron content.

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[1] Metallurgist, Ohio Brass Co., Mansfield, Ohio.

[2] Nomenclature as recommended for this type of alloy by Com. B-2, A. S. T. M.; 1920.

722°—22

I. INTRODUCTION.

The presence of iron in brass is usually objectionable for at least two reasons. First, it ordinarily replaces a much more expensive metal and so, merely from a consideration of the scrap value of the alloy, should be kept as low as possible. Second, the physical properties of such material are noticeably, and in many instances, adversely, affected by the presence of even small amounts of iron. Sometimes iron is intentionally added to brass because the increase in hardness and tensile strength it produces is beneficial in certain special cases. Such alloys are not in general use in this country, however, and their production requires careful supervision and treatment. The usual practice, therefore, is to obviate any possible ill effects from the presence of iron by specifying a low ferrous content. Iron has a particularly harmful influence on the machining qualities of brass, especially when the ferrous metal is not well disseminated throughout the mass. In practice poorly diffused iron sometimes occurs in brass and bronze castings due, in spite of the use of a magnetic separator, to the inadvertent presence of core pins, nails, iron turnings, or similar materials in the scrap metal employed in the melt. Such inclusions naturally cause trouble in machining. A nondestructive method for rapidly and accurately determining the proportion of iron contained as an impurity in cast brass would be, therefore, of considerable value in the industry. With this in mind a study was made, in cooperation with the Ohio Brass Co., of the magnetic properties of a series of samples of tin-red brass contaminated with iron.

The literature seems to be almost silent on this particular problem, most of the investigative work having been done either on iron-rich alloys, or else on metals of the Heusler type. Some data are available, however, on the magnetic properties of binary copper alloys containing no iron [3] and on high zinc brass contaminated with minute quantities of iron.[4] This information may be summarized for the present purpose, however, by the statement that the copper-rich brasses and bronzes, free from iron, are diamagnetic while the 50–50 copper-zinc alloy becomes paramagnetic when 0.023 per cent, or more, of iron is present.

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[3] A. S. Smith, Jour. Franklin Inst., **192**, pp. 69, 157; 1921.

[4] K. Overbeck, Annalen der Physik, **351**, p. 677; 1915.

II. MATERIAL.

The alloy used in this investigation was of the type 82 copper, 15 zinc, and 3 tin. A special series of samples was made up in which the composition, as far as the nonferrous constituents were concerned, was maintained as uniform as possible, while the iron content ranged from scarcely more than a trace up to 0.75 per cent. The copper, zinc, and tin used were good commercial grades.

The metal was cast horizontally into bars, 37 cm (15 inches) long and 1.9 cm (three-fourths inch) in diameter by the Ohio Brass Co. The procedure followed was to melt the electrolytic copper in a crucible then add the tin and zinc. When this metal was ready to pour the iron was introduced as cast-iron turnings, average fineness 54.3, mixed with ammonium chloride. Four bars from each alloy were cast in the same mold and from the same gate. One bar from each mold was then turned down to 1.2 cm (0.5 inch) in diameter and two specimens about 15 cm (6 inches) in length were cut from it.

A charge of between 50 and 100 pounds of metal was used for each pouring and consisted of copper, 80.8; zinc, 16.2; and tin, 3.0 per cent by weight. The excess zinc was added to take care of the usual small loss of this metal by volatilization. About 40 minutes' heating was required to melt the metal and get the alloy ready for pouring at about 1100° C. Chemical analysis showed that the following results were obtained:

TABLE 1.—Iron Content of Specimens.

[Analysis by J. A. Scherrer, associate chemist, Bureau of Standards.]

Specimen.	Iron content.	Specimen.	Iron content.
	Per cent.		Per cent.
1	0.010	5	0.137
2	.065	6	.75
3	.132	7	.35
4	.141		

A quantitative, chemical determination of the nonferrous constituents gave the following averages: Copper, 82.1; tin, 2.89; lead, 0.07; and zinc (by difference), 14.7 per cent. The greatest divergence from these figures was a value of 15.4 per cent for the zinc content of one specimen, a variation of only 0.7 per cent from the mean, so that the composition of the base alloy of the various bars was uniform to a satisfactory degree. If manganese were present in any instance, it might possibly produce a combination

having magnetic properties similar to those of the Heusler alloys. Qualitative tests, however, showed no trace of manganese in any of the samples. The ferrous content was verified in every instance by making another determination on metal from a different part of the specimen. Microscopic examination indicated that the iron present had alloyed with the nonferrous matrix to form about as intimate a mixture as possible in each case. The results from these specimens, therefore, were not complicated by the presence of unalloyed particles of iron.

III. APPARATUS.

The specimens were magnetized in a solenoid 50 cm (20 inches) long. The concentration of the winding was such that the numerical value of the magnetizing force within the middle portion of the solenoid was approximately 100 times that of the current in amperes. The test coil of 1200 turns was wound on a brass form and extended over about two-thirds of the specimen. The readings of magnetic induction were taken by means of a ballistic galvanometer.

On account of the low susceptibility of the brass bars it was necessary to balance out the magnetizing force in order to attain a reasonable degree of accuracy in the measurements. This was done by connecting the primary of a variable mutual inductance in series with the magnetizing coil while the secondary was connected in series opposition with the test coil. A diagram of connections is given in Figure 1. A storage battery, *E*, furnished the magnetizing current, which was regulated by the resistance *R* and measured with an ammeter *A*. The reversing switch, *C*, served to reverse the direction of the magnetizing current when taking a ballistic deflection. *S* is the magnetizing solenoid, with the test coil *TC*, and *M* is the variable mutual inductance. The sensitivity of the galvanometer, *G*, was controlled by means of the series and parallel resistances, *RS* and *RP*. As all of the coils were wound on brass forms, eddy currents were found to be troublesome, giving a double kick upon reversal of the magnetizing current. In order to obviate this difficulty the magnetizing solenoid was surrounded with another coil *D*, which was short-circuited through a resistance. This resistance could be so adjusted as to eliminate the double kick.

The form upon which the test coil was wound was apparently very slightly magnetic and consequently it was necessary to read-

just the mutual inductance for each value of magnetizing current used. The procedure was as follows: First adjust M and D till upon reversal of the magnetizing current there is no deflection of the ballistic galvanometer. Then insert the specimen and note the deflection upon reversal of the current. The deflection is proportional to $B-H$. The galvanometer was calibrated by means of the mutual inductance in the usual way, the connections being changed so that the calibrating current did not flow through the magnetizing solenoid.

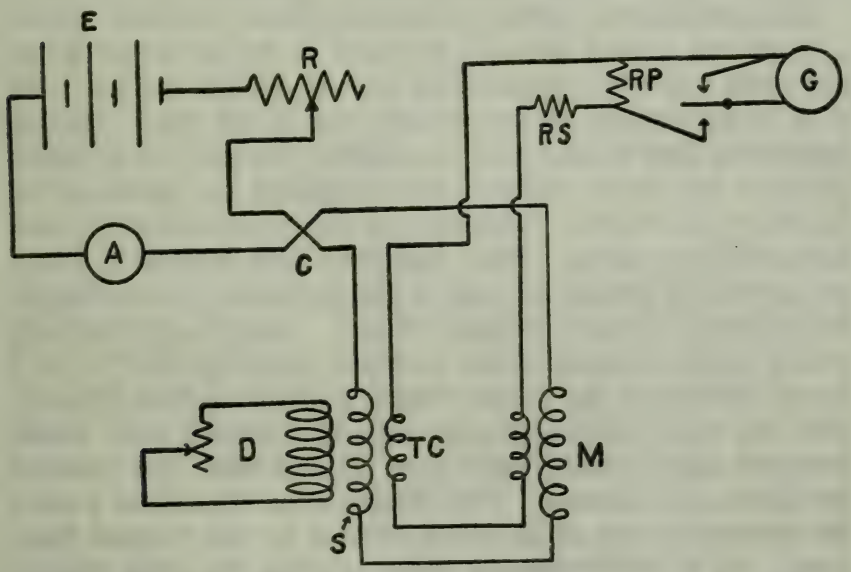


FIG. 1.—*Diagram of connections for apparatus for the magnetic testing of brass bars*

IV. OBSERVATIONS AND RESULTS.

The specimens described above were tested, as cast, with 10 different values of magnetizing force, varying from 25 to 500 gilberts per centimeter. The use of stronger fields was impossible because of the heating of the coils. Samples of the copper and zinc used in preparing the specimens were also tested, but neither they nor the brass bars to which no iron had been intentionally added (specimen 1), gave any readable deflection; so that the method employed, although it would detect susceptibilities as low as 4×10^{-6}, did not indicate paramagnetism in these substances. In the preliminary runs all of the samples were tried out, but the duplicate specimens from the same bar agreed so well that it was considered sufficient, in general, to test only one sample from each

bar. After measurements were made on the specimens in the cast condition, they were annealed; first for 15 minutes at 625° C., then for 8 hours at 800° C., and finally for 8 hours more at 800° C., and cooled slowly with the furnace each time. In the cast condition the samples apparently were quite uniform from one end to the other. After the first 8-hour anneal, however, samples 2, 5, and 7 developed a small difference in susceptibility between the two ends of the bar. This divergence persisted after reannealing. Sample 2 showed the greatest variation, having a difference in susceptibility at the two ends of about 15 per cent.

The accompanying graphs present the results obtained. Figure 2 shows the relation between $B-H$ and H for the alloys in the cast state. H is the magnetizing force in gilberts per cm, while $B-H$ is the increase in flux density due to the brass (metallic induction), and is expressed in gausses. Figure 3 is a similar graph of the results obtained after annealing the specimens for 15 minutes at 625° C. Samples 2, 3, and 7 are noticeably more magnetic than before. Since this brief heat treatment caused an appreciable change in some of the specimens, it was decided to give the bars a more prolonged anneal. Accordingly, they were loosely packed in clean white sand and heated to 800° C. for 8 hours, after which the results shown in Figure 4 were obtained. The thin black scale (averaging 0.04 mm (0.0015 inch) thick), probably cupric oxide, which then covered them was removed by lightly sand blasting. With the exception of numbers 2 and 3 the specimens were all markedly affected by this thermal treatment. As a further heating might produce yet other changes in the magnetic characteristics, a second 8-hour anneal at 800° C. was given them. There was no material change produced, however, and the results are not shown.

V. MICROSTRUCTURE.

Since the condition in which the iron existed in the specimens would markedly influence the magnetic effects, it was essential to learn as much as possible about the constitution of the brass tested. The accompanying photographs are all of specimens taken from sample 6, but sections of all the other specimens were examined as well. Figure 5 (*a*) shows the alloy as cast. The usual dendritic structure of cast metal of this type is the only noticeable feature. Figure 5 (*b*) represents the appearance after annealing for 8 hours at 800° C. The original cored structure has almost disappeared, showing that the matrix of the metal has

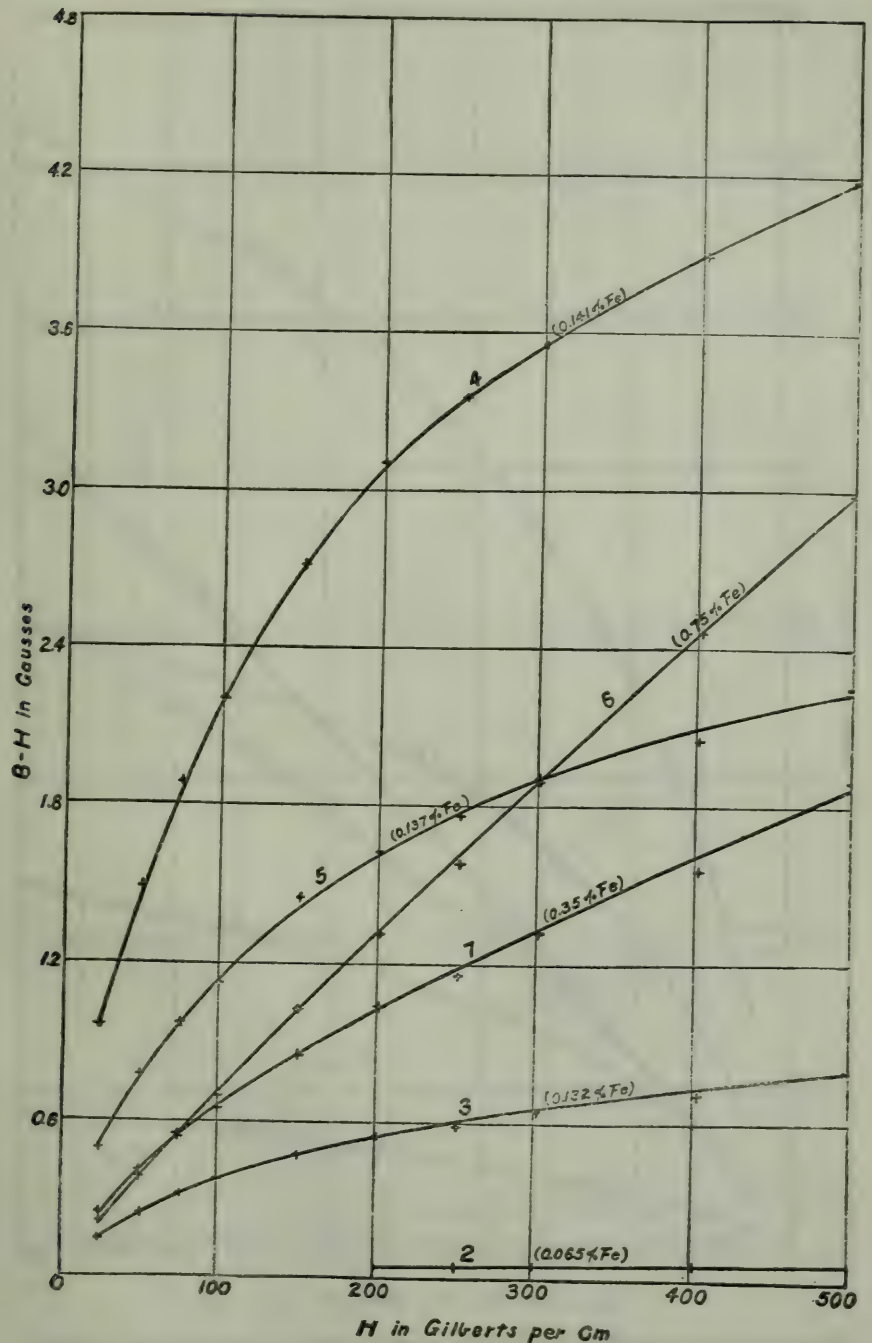


FIG. 2.—*The variation of flux density with magnetizing force for specimens as cast*

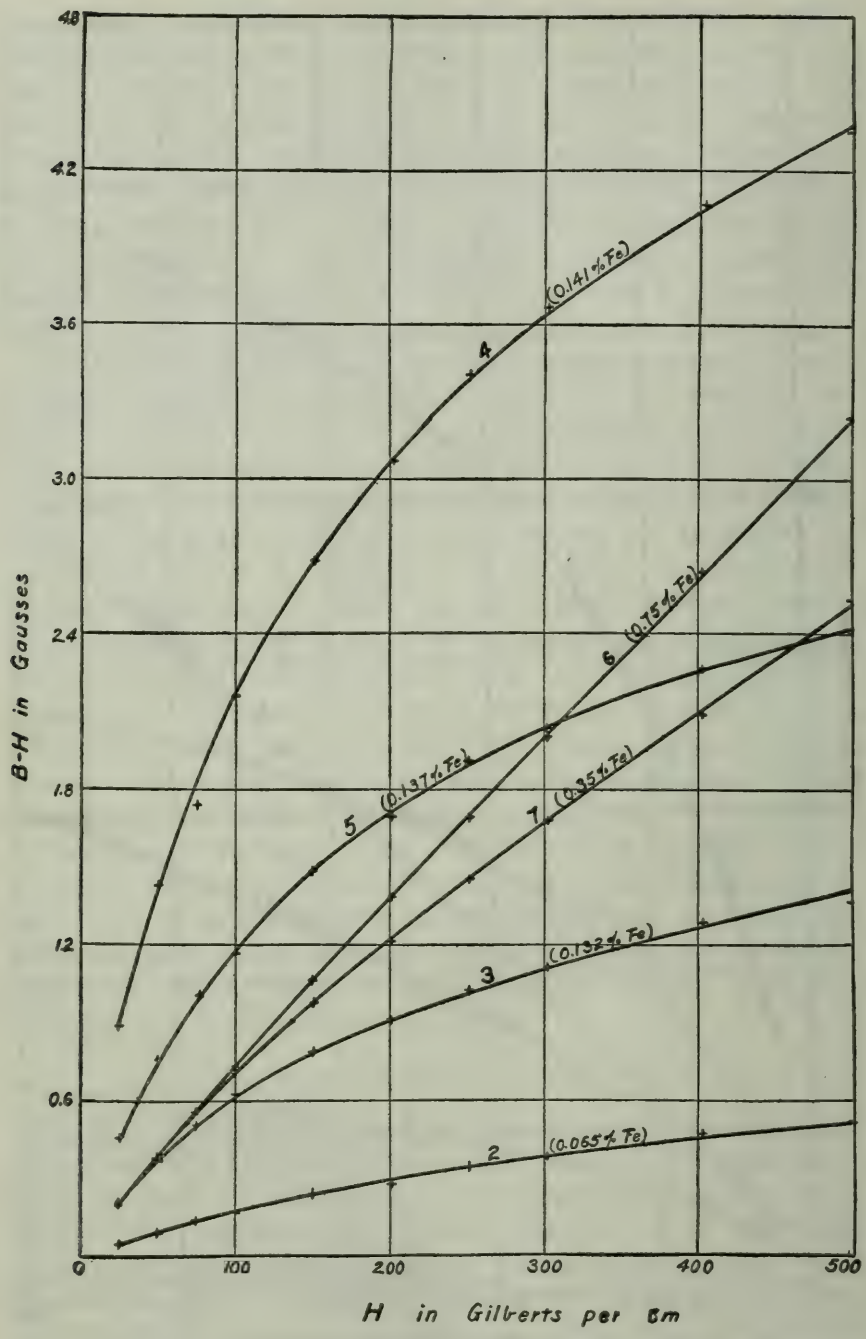


FIG. 3.—*The variation of flux density with magnetizing force for specimens after annealing 15 minutes at 625° C*

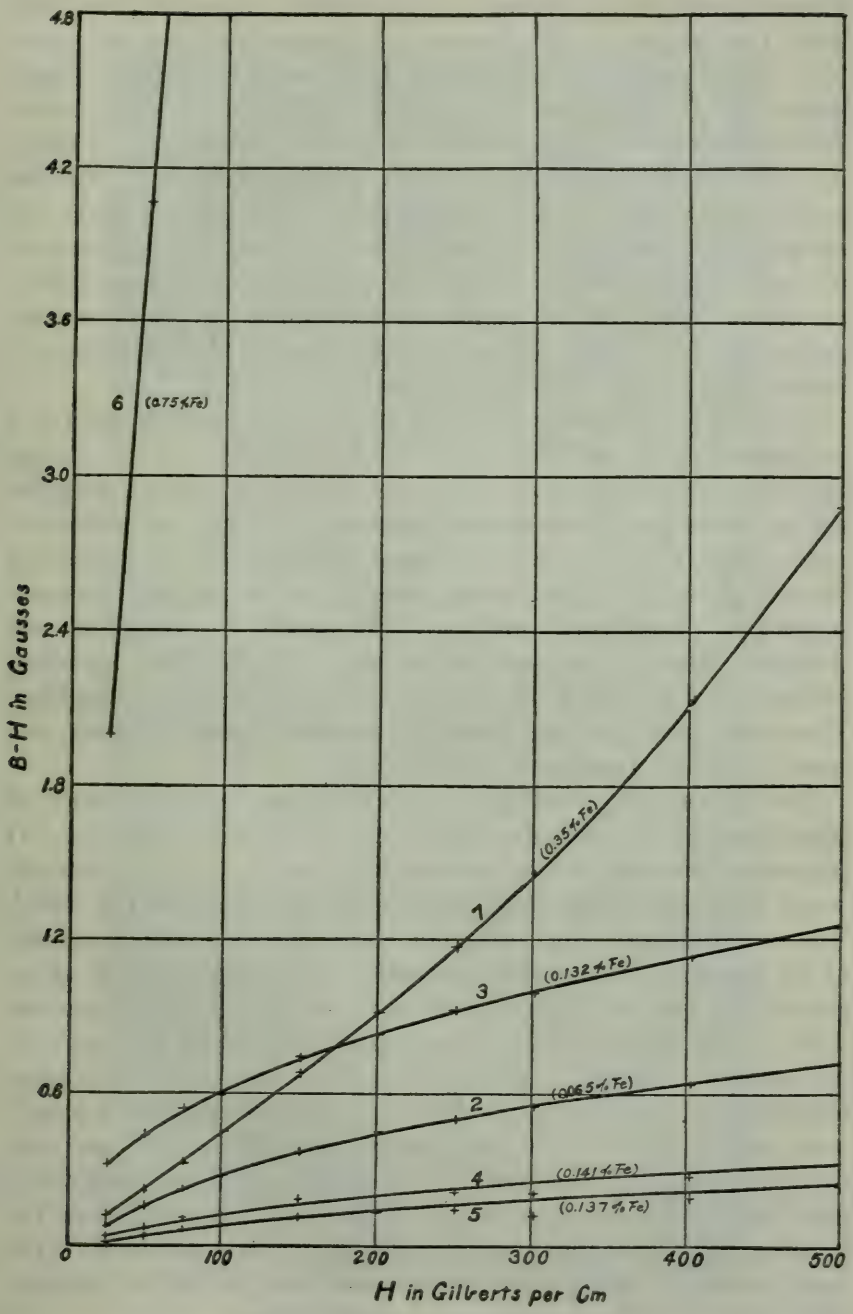


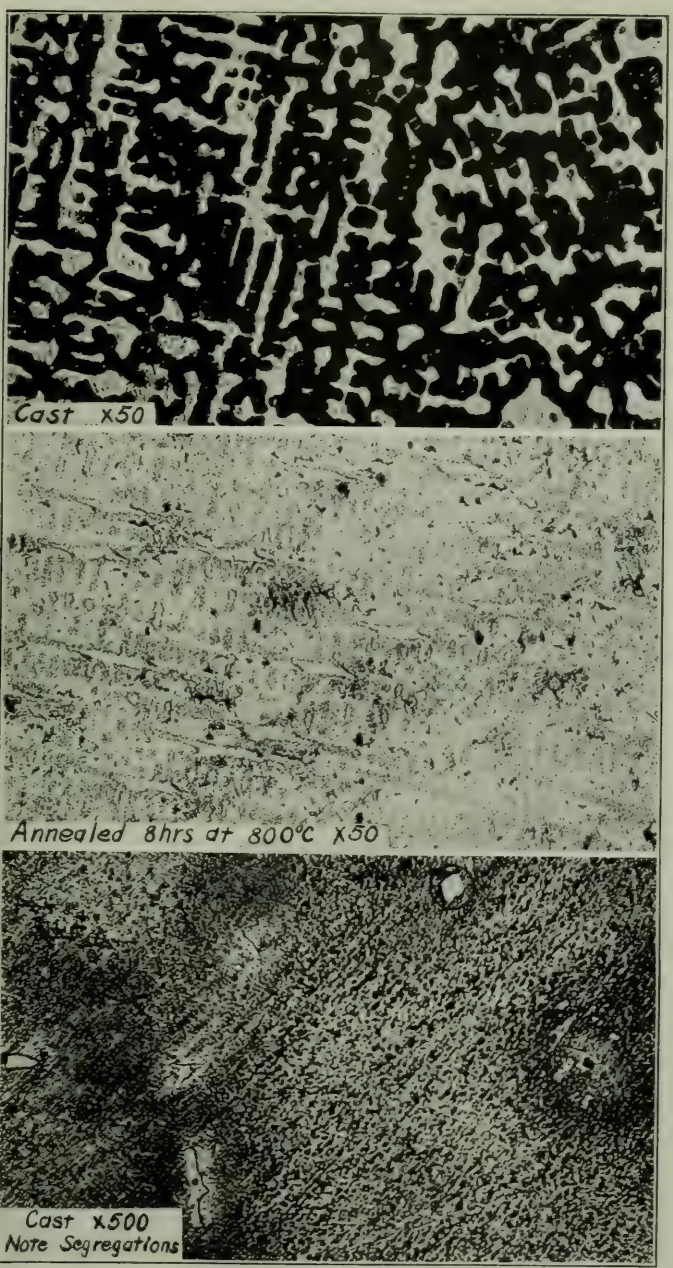
FIG. 4.—*The variation of flux density with magnetizing force for specimens after annealing 8 hours at 800° C*

become much more uniform in composition. A very thin outside layer (not shown in the picture), in general less than 0.25 mm (0.01 inch) thick, recrystallized into small polygonal grains similar to those formed in worked and annealed alpha brass. This behavior was due to the straining of the outer skin of metal by the cutting tool in turning the specimens to size. Further annealing did not change the structure appreciably. All of the samples contained the numerous dark areas frequently attenuated into mere lines, noticeable in this view (Fig. 5 (*b*)). These defects are due to oxide inclusions, shrinkage cavities, or gas evolution during the freezing of the metal. At this low magnification (50 diameters) no trace of iron was found.

Figure 5 (*c*) shows the structure of the cast sample as seen at a magnification of 500 diameters. The light area inclosed in the circle is an iron segregation, while the other light-colored, irregular shaped areas are the eutectoid resulting from the interaction of copper and tin. There is no great difficulty in distinguishing between these two constituents, since the ferrous aggregates are a somewhat darker shade of gray and, unlike the eutectoid, are sharply outlined in the unetched samples. Some minute zinc oxide inclusions[5] were visible in each of the specimens before etching. They were darker in color than the iron segregations, however, and were frequently associated with cavities.

The information available in the literature as to the mode of occurrence of iron in brass and bronze is not very extensive. It is known, however, that a certain small amount, 0.35 per cent in 70–30 brass,[6] goes into solid solution in the matrix of the metal. When present in larger quantities than this, pale, rounded areas of an iron-rich constituent make their appearance. Iron, as an impurity in gun metal (88 copper, 10 tin, 2 zinc), is said to combine with tin and separate out in hard masses,[7] even as little as 0.11 per cent iron making itself known in this way.[8] In the present investigation iron-rich areas, frequently almost circular in shape, were observed only in those samples containing 0.137 per cent or more of iron. These ferrous segregations were quite uniformly distributed over the cross section of the specimen, and since the number and size of these areas increased proportionately with the iron content, it was possible to estimate roughly the per cent of iron present from the microscopic examination.

[5] Comstock, Jour. Am. Inst. of Metals, **12**, p. 5, 1918; or Foundry, **47**, p. 79, 1919.
[6] Smalley, Metal Industry (London), **17**, p. 421; 1920.
[7] Dewrance, Journ. Inst. of Metals (British), **11**, p. 214; 1914.
[8] Primrose, Metal Industry (London), **12**, p. 437; 1918.



a

b

c

FIG. 5.—*Microstructure of specimen 6 (0.75 per cent iron) after etching with ammonium hydroxide plus hydrogen peroxide.*

The cored structure of the cast metal largely disappears on annealing. At the higher magnification the iron segregation, inclosed in a circle, and the other light irregular-shaped areas, due to the eutectoid, can be distinguished.

After annealing for 8 hours at 800° C. the eutectoid almost entirely disappeared but the iron-rich constituent was not noticeably affected. In fact, a sample of the brass containing 0.75 per cent iron was heated to 900° C., held there 30 minutes, and quenched in water without any appreciable influence on the ferrous aggregate. On the other hand, when a similar sample was heated to 950° C. and quenched, the iron-rich areas disappeared. They made their appearance again, however, on reheating to the same temperature and cooling slowly. From this behavior it may be seen that these areas do, indeed, represent an iron-rich constituent and not simply particles of undissolved iron. These ferrous areas were identified in a specimen which contained only 0.137 per cent iron and had been heated to 950° C. and very slowly cooled. The solubility of iron in this type of brass is, therefore, less than 0.14 per cent.

As a result of some experimental work on brasses containing iron Smalley [9] concluded that the presence of small amounts of iron produces a finer grain size in alpha brass, both in the cast condition and after it has been worked and annealed. A careful examination of the present series of specimens, however, failed to reveal any definite difference in crystal size that could be attributed to the variation in iron content. The metal of bar 3, at the end farthest from the pouring gate and, therefore, more quickly cooled than the rest of the specimen, was finely crystalline in structure. The end near the gate, nevertheless, contained the usual coarse dendrites. Bar 3 was poured at 1040° C., or about 60° C. below the average casting temperature of these specimens, so that this low temperature, coupled with the chilling effect encountered at the outer end of the bar, may reasonably be accepted as the real cause of the formation of the small crystals. This variation in grain size did not result in any marked difference in the magnetic properties of the two ends of the specimen.

VI. DISCUSSION.

An examination of the data presented graphically above reveals several interesting points. For instance, Figure 3 shows that the magnetic susceptibility of the cast metal does not vary directly with the iron content. Not only do the curves from the samples of high and low ferrous content seem to be indiscriminately mixed, but their slopes also vary, frequently causing them to cross each

[9] See footnote 6.

other. Then Figures 3 and 4 show that the magnetic properties of the specimens are markedly affected by the changes in physical condition as influenced by heat treatment. Concrete evidence of this fact is furnished by the change in numbers 2 and 3 in the 15-minute anneal and the general shift in the characteristics of almost all the samples in the subsequent 8-hour anneal. Yet it is evident from Figure 4 that, even after this prolonged heating, the susceptibility can not be taken as an index of the iron content.

Figure 6, in which the magnetic susceptibility is plotted against iron content, distinctly shows their lack of correlation. In the cast condition, particularly, there seems to be no direct relation-

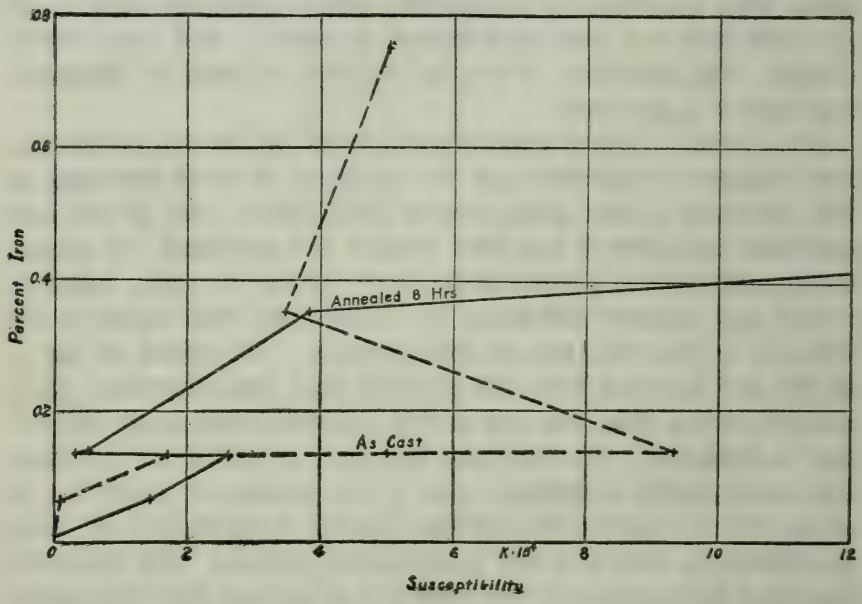


FIG. 6.—*The variation of magnetic susceptibility with iron content H=300*

ship. The determined points approach a smooth curve much more closely, however, after the specimens have been annealed for 8 hours. Besides this, the break in the curve at 0.14 per cent iron coincides with the initial appearance of the iron-rich constituent in the structure of the metal. The microscopic examination indicated that up to 0.14 per cent the iron occurred as a solid solution in the matrix of the alloy, but with higher ferrous content iron-rich aggregates were also present. The absence of a direct relationship between iron content and magnetic properties is not difficult to account for in view of the two conditions thus shown to exist. The mere difference in the mode of distribution of the iron

would account for wide variations in the observed values of magnetic susceptibility even though the iron had intrinsically identical magnetic properties in the two cases. This is due to the unequal self-demagnetizing effect of ferrous aggregates of different dimensions. The presence of unalloyed iron particles would complicate matters still further. The apparent discontinuity at 0.14 per cent iron can probably be traced to the appearance of the iron-rich constituent previously described.

From the above considerations an explanation of the seeming vagaries of the two curves of Figure 6 can be offered. The points determined for the cast metal did not lie on a smooth curve, because the metal in this case was not representative of equilibrium conditions since the relatively rapid rate of cooling from the casting temperature did not permit a uniform distribution of the constituents of the alloy. This lack of homogeneity resulted in abnormal magnetic properties. The graph of the susceptibility of the annealed samples, on the other hand, may be considered as being made up of two fairly smooth curves. The first, extending from 0 to 0.14 per cent iron, obtains for the condition that the ferrous impurity is all in solid solution. The second, for iron contents of 0.14 per cent or more, applies to those cases where the iron-rich constituent is present. While it is recognized that more extensive data are necessary to really prove this matter of a double curve for the annealed metal, such work was felt to be outside the scope of the present investigation which was primarily concerned with cast brass.

One interesting point to be noted is the change in curvature of the graphs for bar No. 7. It is seen that in Figure 2, for the cast condition, the curve for this specimen is convex upward; while the graph for the same sample after the 8-hour anneal (Fig. 4) is convex downward. In the first case, therefore, the susceptibility decreases with increasing values of magnetizing force, but in the second case it increases.

The iron present in the alloys examined is undoubtedly the cause of the observed magnetic properties since a qualitative test for manganese, which is the essential constituent of the nonferrous magnetic alloys, failed to indicate a trace of this element. In addition to this fact, the iron-free samples were not sufficiently magnetic to evidence a susceptibility that could be measured with the apparatus employed. For iron contents of 0.06 per cent or more, however, an indication was always obtained.

VII. SUMMARY.

The presence of iron in commercial brass is often objectionable, particularly if it occurs as discrete, poorly alloyed particles. In order to obviate any such harmful effects, a very low ferrous content is frequently specified. Therefore, a rapid, nondestructive method for quantitatively determining its presence would be of great value in practice. A magnetic method of inspection would fulfill the requirements of such a test if a definite relationship exists between some magnetic property and the iron content of the metal. With these facts in mind a study was made of the magnetic characteristics of cast, tin-red brass contaminated with iron.

A series of samples was prepared containing various small proportions of iron up to 0.75 per cent. A small quantity, less than 0.14 per cent, of the iron went into solid solution, but when amounts greater than this were present, an iron-rich constituent made its appearance as pale, rounded areas. The iron content had no noticeable effect on the grain size of the brass.

Magnetic properties were determined in the cast condition and after being annealed 15 minutes at 625° C., 8 hours at 800° C., and 16 hours at 800° C.

From the results of this investigation the following conclusions seem to be warranted:

1. The magnetic properties are not a precise index of the iron content of the cast metal.

2. The magnetic susceptibility is markedly affected by changes in physical condition produced by heat treatment.

3. After the material has been thoroughly annealed there is still no simple relationship between the magnetic susceptibility and the iron content.

WASHINGTON, June 15, 1922.

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RELATIVE USEFULNESS OF GASES OF DIFFERENT HEATING VALUE AND ADJUSTMENTS OF BURNERS FOR CHANGES IN HEATING VALUE AND SPECIFIC GRAVITY

BY

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RELATIVE USEFULNESS OF GASES OF DIFFERENT HEATING VALUE AND ADJUSTMENTS OF BURNERS FOR CHANGES IN HEATING VALUE AND SPECIFIC GRAVITY.

By Walter M. Berry, I. V. Brumbaugh, J. H. Eiseman, G. F. Moulton, and G. B. Shawn.

ABSTRACT.

In connection with an investigation conducted by the Public Service Commission of Maryland to determine the most economic heating value standard for manufactured gas in the city of Baltimore, the Bureau of Standards conducted an extensive series of laboratory tests to determine primarily: (1) The relative utilization efficiency of gases of different heating value; (2) the extent to which present appliances can be adapted to give good and efficient service with gases of different heating value and composition; and (3) what adjustment in appliances is necessary to give the consumers good and efficient service when different kinds of gases are mixed and there is a variation in the composition, heating value, and the specific gravity of the gas.

The laboratory tests of gases varying in heating value from 300 to 600 B. t. u./ft.^{3} indicated that *the usefulness for top burner cooking is dependent almost wholly upon the total heating value per cubic foot.*

Some change in size of orifice and air-shutter adjustment of burners is necessary to secure the best service when a material change is made in heating value. Most existing burners can be readily adjusted to give good service with heating values as low as 450 B. t. u./ft.^{3} without alterations of the burners.

Uniformity in heating value, specific gravity, and pressure are essential for the very best service, yet it is practicable to adjust burners to give satisfactory service in cities where different gases are mixed and there is considerable variation in the heating value or specific gravity.

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I. INTRODUCTION.

1. PURPOSE OF INVESTIGATION.

Reductions in heating value standards in many of our cities within the past two or three years are claimed to have brought about material savings in the cost of manufacture of gas and lower prices to the consumer than if the former standards had been continued. However, the reductions in standards have not always been brought about without some complaint from the consumers that the service was inferior and the total cost greater with a lower-heating value gas than with a gas of higher-heating value.

The Public Service Commission of Maryland has undertaken to investigate this matter very fully, with a view of determining the most economic and satisfactory heating-value standard for the city of Baltimore. In connection with this investigation the commission requested the Bureau of Standards to make laboratory tests to determine the relative efficiency of gases of different heating value and the adaptability of existing appliances for gases differing in heating value and composition.

While the effort was made to have the tests of the relative efficiency of gases of different heating value as practical as possible, it should be appreciated that it is exceedingly difficult to obtain

conditions in the laboratory exactly comparable with those of the average consumer's home. Waste of gas is naturally eliminated in laboratory tests. A definite size of cooking vessel must be used in order to obtain comparable results which have any value. The utensils are clean and in good condition, as is also the stove. Finally, the tests are necessarily limited to the heating of water on top burners; and while this gives an exceedingly valuable indication, it is not necessarily a conclusive proof of the relative quantities of gas of different qualities which will be used by the conconsumers. In fact, the actual data on change of consumption of gas where change in calorific value has been made do not give results agreeing exactly with conclusions which might be drawn from laboratory tests. Due weight should be given to this practical data in drawing any final conclusions.

The question of the relative utilization efficiency of gases of different heating values has been under consideration for several years, both in England and in this country. Exhaustive laboratory tests have been conducted on this subject by the Gas Investigation Committee of the British Institution of Gas Engineers and the Joint Committee on Efficiency and Economy of Gas of the California Railroad Commission.[1] Although the conclusions from the previous laboratory tests have been generally in agreement, it was thought highly desirable to duplicate some of the tests with the gases available in Baltimore and establish carefully the conditions under which the appliances would give the maximum practical efficiency with each kind of gas.

The gas engineering section of the Bureau of Standards has been conducting tests of manufactured and natural gases for several years, and since it had a trained personnel and special testing equipment for studying the combustion of gases, it undertook to make the required laboratory tests, which form one part of the commission's investigation.

In this report the bureau gives the results of tests which show the relative efficiency of utilization of gases of different heating values and composition. The results show also the pressure required to operate the burners, and how appliances can be adapted and adjusted to give satisfactory service with gases of different heating value and specific gravity. The data showing how to adjust appliances to give good service where the relative

[1] Report of the research subcommittee of the gas investigation committee of Institution of Gas Engineers (England), Gas Journal, Oct. 29, 1918; Nov. 5, 1918. Progress report of Joint Committee on Efficiency and Economy of Gas of the Railroad Commission of the State of California, Gas Age-Record, Nov. 12, 1921; Nov. 19, 1921.

proportions of coal or coke-oven gas and water gas vary should have considerable practical value in many localities.

Baltimore is supplied at the present time with gas having a heating value of 500 B. t. u./ft.^{3}. A portion of the gas is coke-oven gas, purchased by the Consolidated Gas, Electric Light & Power Co. from the Sparrows Point plant of the Bethlehem Steel Co. The latter company is a commercial concern not subject to commission regulation and sells its gas merely as a by-product. The remainder of the supply is water gas, manufactured at the Spring Gardens plant of the Consolidated Gas, Electric Light & Power Co. The standard of heating value in Baltimore was reduced to 500 B. t. u. in June, 1920, in order to allow the economical distribution of the coke-oven gas, which has normally a heating value of about 500 B. t. u.

2. SCOPE OF THE LABORATORY TESTS.

The laboratory work in Baltimore was divided into three parts, as follows:

(1) The first series consisted of numerous practical efficiency tests made with 10 different kinds of gas when the gas rate and air shutter were adjusted in each case to produce a good flame. These tests were made on two different ranges and the results show the efficiency, the time required, and cubic feet of gas used to bring 2 quarts of water to boiling from an initial temperature of 80° F.

In order to gather information on the composition of the combustible mixture within the burner at the condition of good adjustment for each gas, the burner was removed from the range after each adjustment and connected to special apparatus which had been developed for that purpose.

The condition at which the flash back and the blowing from the ports occur with each kind of gas represents a rather definite relation between velocity through the ports and composition of the air-gas mixture. The yellow tips also occur at rather definite mixtures of gas and air. These conditions were also determined with the above-mentioned apparatus.

(2) The principal object of the second series of tests was to establish more definitely the workable limits of operation of burners with gases of different heating value and specific gravity. This part of the laboratory schedule consisted of a series of tests made with water gas of 400, 500, and 600 B. t. u. and coal gas of 525 B. t. u. With each kind of water gas the burner was operated at three rates of consumption, namely, 7,000, 9,000, and 11,000

B. t. u./hr. The cone and flame heights and the limits of adjustment within which the burner could be satisfactorily operated were observed.

This matter of correct appliance adjustment is of considerable importance in cities where coke-oven or coal gas and water gas are mixed. As a result of the daily and seasonal variations in demand it is difficult to maintain the ratio of the two gases constant and, therefore, there may be considerable variation in the specific gravity of the gas with a resulting change in air entrainment and variation in flame characteristics.

(3) The third part of the investigation consisted of a series of tests with water gas of 500 and 600 B. t. u./ft.^{3} to determine the position of vessel relative to the gas burner that would give the highest thermal efficiency without forming dangerous quantities of carbon monoxide. In these tests the utensil was placed at distances of 1½, 1¼, 1, and ¾ inches from the burner. Tests were made with three gas rates, 7,000, 9,000, and 11,000 B. t. u./hr.

The efficiency that can be secured in top-burner cooking will depend upon the distance of burner from the utensil and upon the flame characteristics. Good flame contact is essential for rapid heating (the consumer's idea of good service) and high efficiency, but the smothering of the flame is dangerous on account of the production of carbon monoxide. At each rate and at each position of vessel the flame was adjusted for three different conditions, namely, a hard flame, a medium flame, and a soft flame. A large number of carbon-monoxide determinations were made under each condition of operation with the ordinary star and disk types of burners. The results of the tests show how the production of carbon monoxide is affected by a change in the distance between the burner and the vessel, variation in rate of gas consumption, or use of different types of burners.

II. PREPARATION OF GAS SAMPLES OF DIFFERENT HEATING VALUES.

In order that a sufficient volume of gas of a constant heating value be available for a series of tests a gas holder with a capacity of approximately 300 feet^3 was secured. For purification purposes the gas before entering the holder was passed through the tar scrubber and purifier shown in Figure 1. The tar scrubber was 2½ feet in diameter and 12 feet high and was filled with dry wood shavings. This scrubber completely removed all the tar in the gas. The purifier, 2½ feet in diameter and 3 feet high, was

FIG. 1.—*View of tar scrubber (1), purifier (2), and gas holder (3) used in these tests.*

filled with iron oxide and wood shavings, which completely removed all traces of hydrogen sulphide.

The city gas used in our tests was piped to our holder direct from the Consolidated Gas, Electric Light & Power Co.'s city distribution line. This gas contained approximately one-third coke-oven gas and two-thirds water gas and the heating value was approximately 500 B. t. u./ft.^{3}

The coke-oven gas was received from the Sparrows Point plant of the Bethlehem Steel Co. The gas as received at Baltimore was free of tar but not of hydrogen sulphide, and it was necessary to purify it before entering our holder. The coke-oven gas used in these tests had a heating value of about 450 B. t. u./ft.^{3}

Coal gas, a gas similar to coke-oven gas but usually of somewhat higher heating value, was secured from the Philadelphia Gas Works, since there were no facilities for its manufacture in Baltimore. It was compressed and shipped in high-pressure cylinders. The heating value of the gas was about 525 B. t. u./ft.^{3} when released into our holder. The gas as received was free of tar and hydrogen sulphide.

All of the water gas was manufactured at the Spring Gardens plant. A connection was made to the outlet of the wash box of a generator set and from there the gas was piped about 400 feet through a 4-inch line to a tar scrubber, purifier, and finally into the gas holder. Gases of different heating values were made by varying the quantity of gas oil sprayed into the carbureter.

III. DESCRIPTION OF APPARATUS AND METHODS USED IN TESTING.

1. TYPES OF BURNERS AND RANGES USED IN TESTING.

In the tests of this report three different designs of top burners were used and are shown in Figure 2. These burners are known as regular front top burners and are often designated as "standard" size (about 4 inches in diameter) to differentiate them from other sizes. Gas ranges of average size are generally equipped with three regular, one giant, and one simmering burner.

Burner No. 1 was selected because it is the most extensively used in Baltimore and also represents the "star" type of burner.

Burner No. 2 which is of the "disk" type, was selected because it was desired to test a burner of an old design, many of which are still in service in Baltimore.

Burner No. 3 was used only in the study of the effect on efficiency with a change of distance of utensil from burner. It is one of the

later designs of the "disk" type of burner and is much used in New York City.

The ranges which were used to determine the efficiency of gases of different heating values are shown in Figures 3 and 4, respectively. They were obtained from consumers' premises where new ranges had been purchased.

2. KIND OF UTENSIL USED.

In this investigation no attempt has been made to study the effect on the efficiency if the size or shape of the utensil, relative to the size of the burner, is varied, nor the probable change in efficiency that would result from the use of utensils made from various materials or those made with different weights of material. A light-weight aluminum utensil was selected such as that shown in Figure 6. It is model No. 44–A made by the Aladdin Aluminum Co. The maximum diameter is 8.1 inches and the capacity is 4 quarts. This size of utensil was used in all the efficiency tests here reported.

3. HOW THE RELATIVE EFFICIENCY OF THE GASES WAS DETERMINED.

In past investigations of this bureau, tests of efficiency of heating were made by heating a given weight of water through a temperature rise of 100° F. Before adopting the method used in this investigation, tests were made to ascertain the difference in efficiency, if any, between heating water from tap-water temperature through 100 ° F. rise or from tap-water temperature to boiling. The effect of stirring the water during heating was also determined. The results were as follows: Two quarts of water heated to boiling, *stirred*, gave 36.8 per cent efficiency; 2 quarts of water heated to boiling, *not stirred*, gave 36.5 per cent efficiency; and 2 quarts of water heated through 100° F. gave 37.5 per cent efficiency.

It is apparent from the above that stirring the water does not appreciably alter the efficiency, nor is the efficiency of heat absorption much different whether the water is heated over a greater or less difference in temperature.

It is also of interest to know whether the rate of heat absorption is constant from the time the utensil is placed over the burner until boiling begins. The curves of Figure 5 show that the rate of heat absorption is constant and depends directly upon the rate of supply of heat.

To make the tests here reported the following method was selected. Two quarts (4.17 pounds) of water were heated from

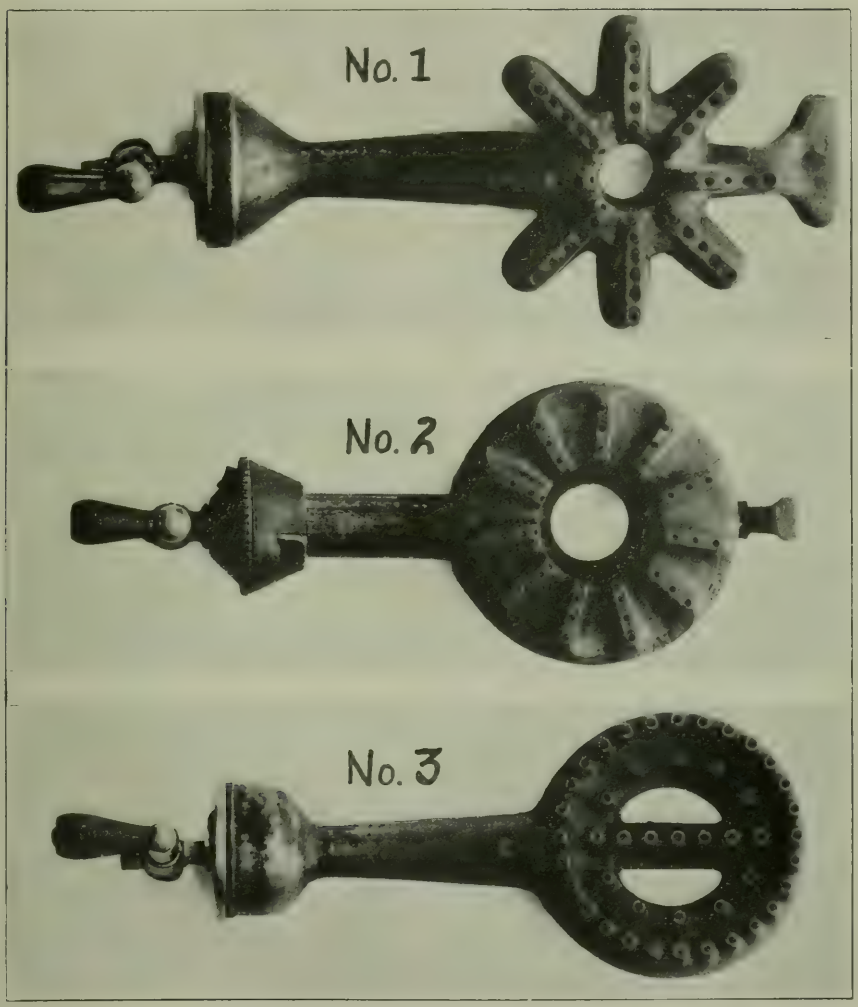

FIG. 2.—*Top view of burners used in the tests.*

Burner No. 1 "star" type, burner No. 2 old "disk" type, and burner No. 3 new "disk" type.

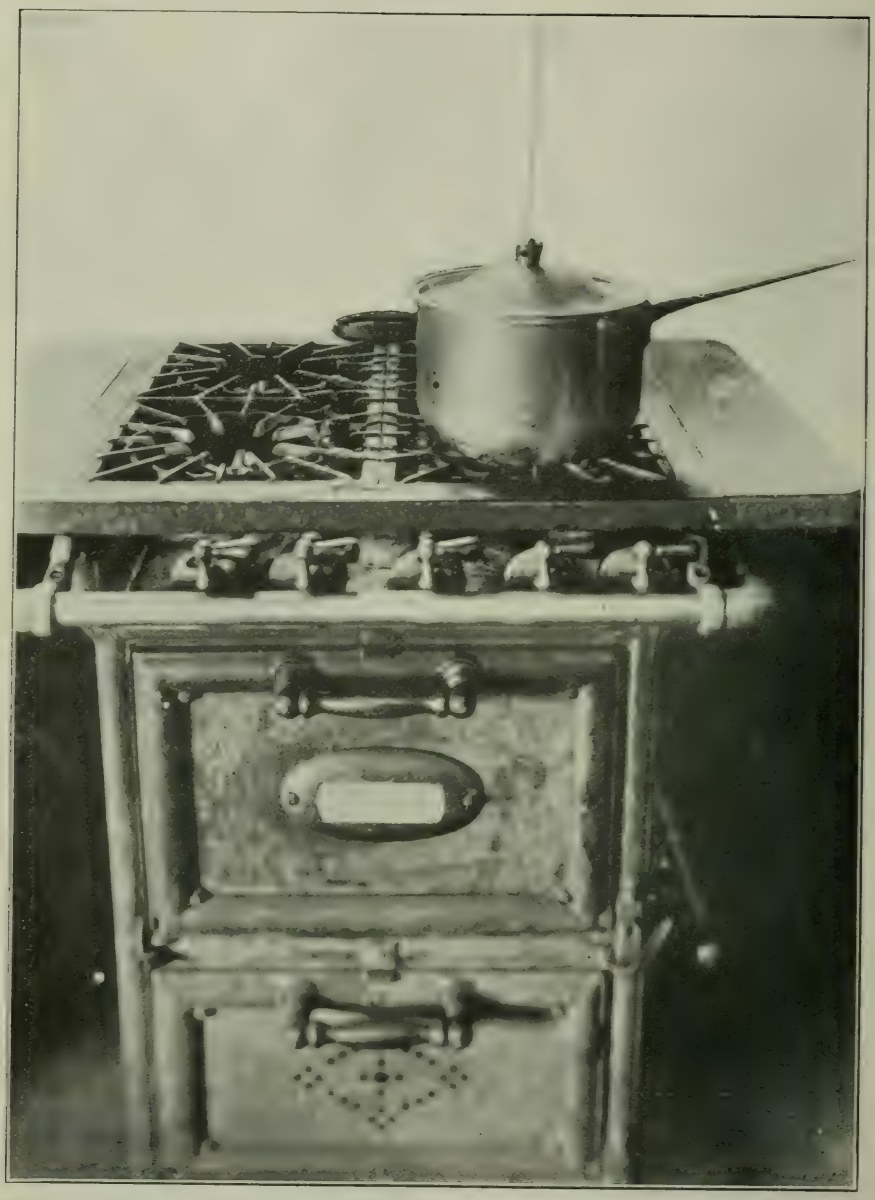

FIG. 3.—*Gas range equipped with burner No. 1 showing utensil used in efficiency tests.*

tap-water temperature to boiling. The initial temperature was very carefully noted just before the utensil was placed over the burner. At the instant the utensil was placed over the burner the gas meter reading was taken. The observer who placed the utensil over the burner watched the water temperature until it just reached the boiling point when he signaled to the person who read the gas meter.

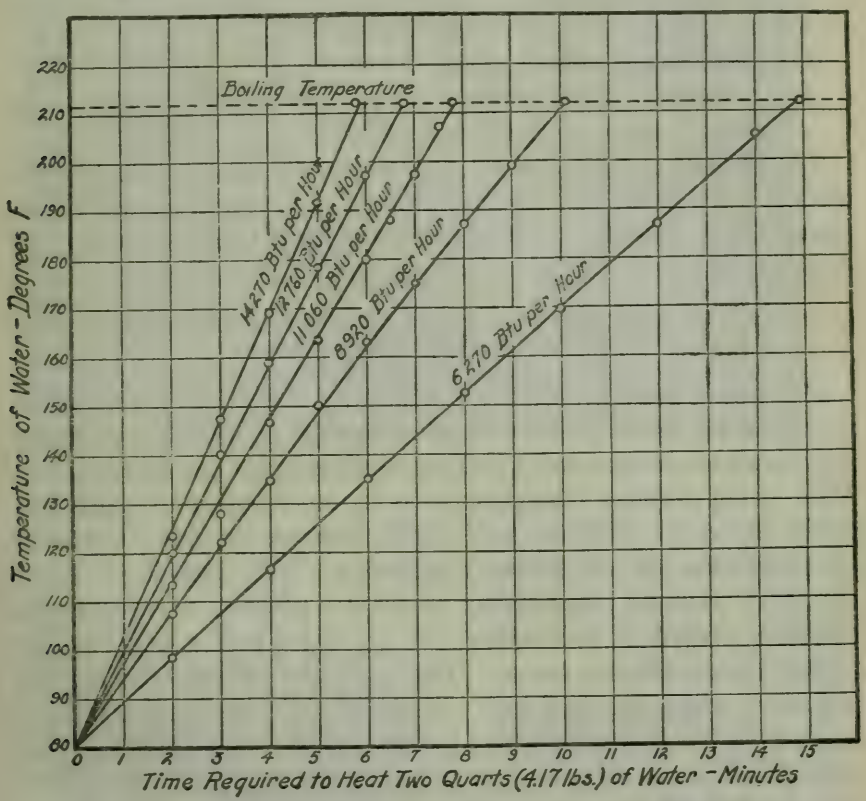

FIG. 5.—*Curves showing the variation of rate of heating water with different B. t. u. rates.*

Burner No. 1 was used to make the tests and was placed 1⅜ inches from the utensil shown in Fig. 3.

During a test the gas temperature, the pressure of the gas in the meter, and the barometric pressure were noted. The difference between the meter readings at the time the utensil was placed over the burner and at the time the water reached 212° F. gave the uncorrected volume in cubic feet of gas consumed. This volume was then corrected to the standard barometric condition of 30 inches of mercury pressure at 60° F. The efficiency was calculated on the basis of the quantity of heat absorbed by the water relative to the total quantity of heat contained in the gas con-

sumed. No allowance was made for the heat absorbed by the utensil. The efficiency may, therefore, be computed from the simple equation,

$$\text{Efficiency} = \frac{W \times T}{\text{B. t. u. per cubic foot} \times V \times F}$$

where

W = weight of water, 4.17 pounds (2 quarts) in the case of the tests of this report.

T = temperature rise of water, degrees F.

V = uncorrected volume of gas consumed.

F = correction factor which reduces uncorrected volume to 30 inches of mercury pressure at 60° F.

The efficiency values shown in this paper are an average of two tests at each position. By making two tests errors in reading the gas meter or the thermometer or in weighing the water would be detected.

4. APPARATUS AND METHOD USED TO TEST THE OPERATION OF BURNERS WITH DIFFERENT GASES.

The set-up used in making the tests of operation of burners is shown in Figure 6. There are two meters, a 5-light wet meter used to meter the gas and a 10-light wet meter for metering the air. After being metered, the gas passes by an opening to a gas bag which serves to eliminate any slight pressure irregularity due to the operation of the meter mechanism. The gas then passes through a pressure regulator by which it is possible to regulate the pressure desired at the orifice. A regulator and a gas bag are placed before the air meter. The regulator reduces the air-line pressure, while the gas bag removes some of the fluctuations caused by the air compressor. Between the air meter and the connection to the wooden box is another gas bag which removes the remaining fluctuations in the air line. After this gas bag is a valve which is used to regulate the flow of air. The mixer portion of the gas burner is sealed in the end of the box opposite the point at which the gas line enters. The gas-line pressure is taken at a point just back of the orifice and is connected to a pressure gauge outside of the box. The air line is joined to the box directly above the point at which the gas line enters. A baffle is placed in front of the air inlet in order to reduce the velocity of the air as it enters the box. The box has a removable lid and is made air-tight. On one side of the box a hole 6 inches square is cut, and a piece of shellacked paper is glued over the opening to form an explosion

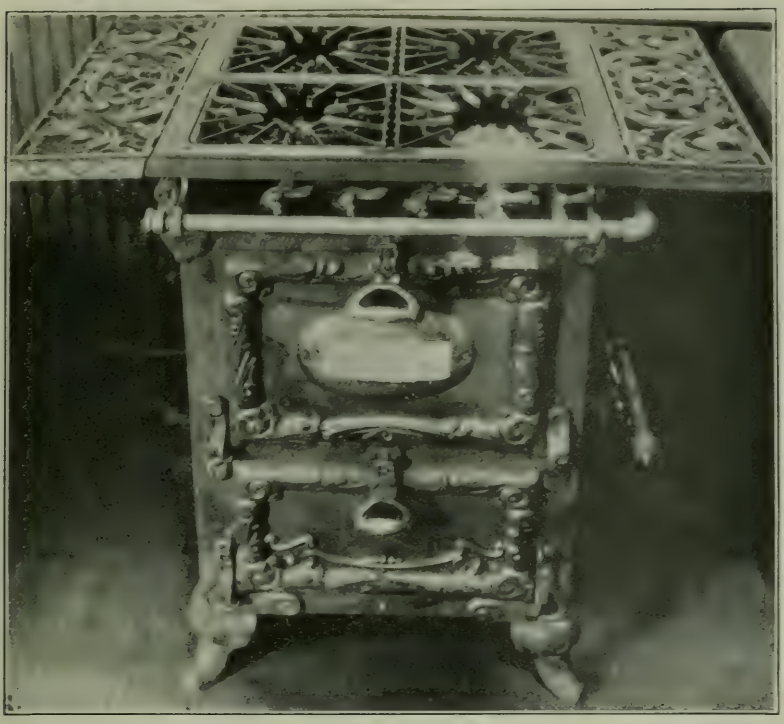

FIG. 4.—*Gas range equipped with burner No. 2 used in efficiency tests.*

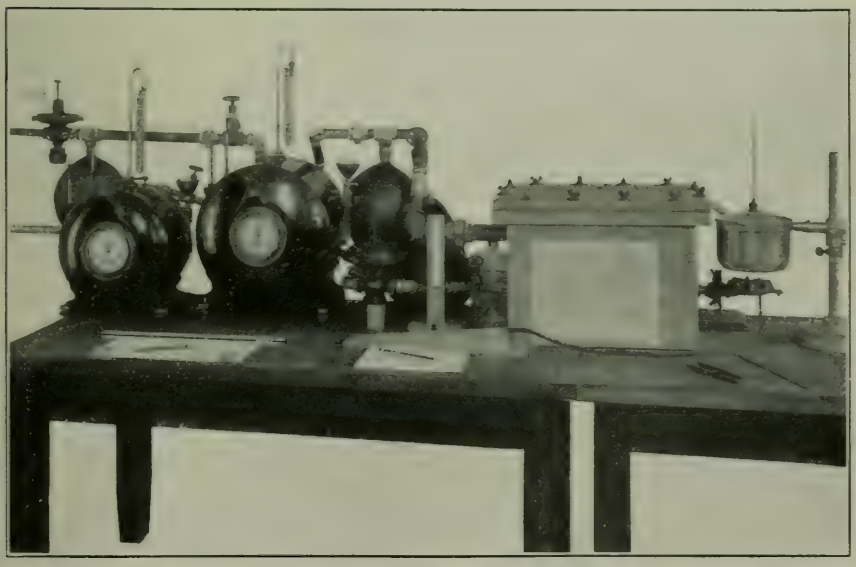

FIG. 6.—*Apparatus used to determine the primary air that was injected into a burner at any condition of operation.*

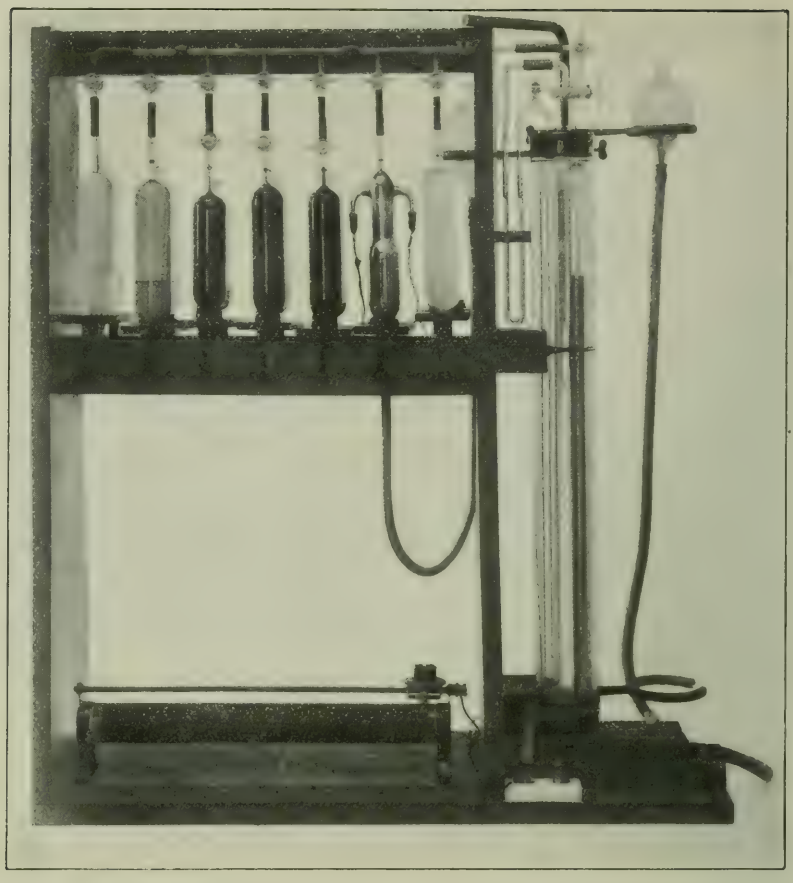

FIG. 7.—*Orsat gas analysis apparatus used to determine the constituents of the gases.*

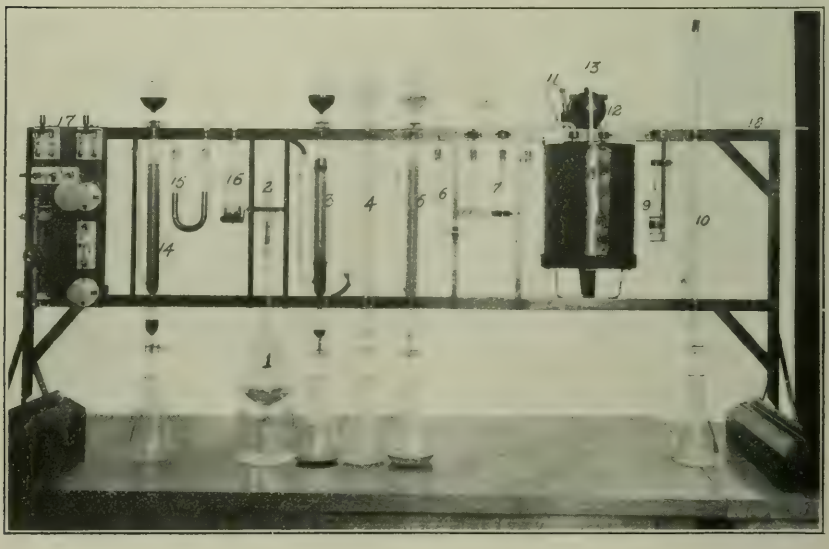

FIG. 8.—*Apparatus used for analyzing products of combustion for carbon monoxide.*

head. A very sensitive slope U gauge is constructed to measure the extremely minute pressures that occur in the burner. Xylene is used in this gauge because it does not adhere to the wall of the U tube.

With the apparatus which has been described it is possible to produce in the burner any desired air-gas mixture. Because it is impossible to operate a burner above an air-gas ratio that will cause the flames to leave the ports or flash back into the burner, and it is impracticable to operate the burner with a primary air-gas ratio which produces a yellow flame, these conditions were determined when testing a burner. To make the tests, the lid was placed on the box, and air was metered into the box at rates which produced these conditions for different gas rates. The ratio of the volume of air to the volume of gas that entered the burner was readily calulated by timing the two meters.

The amount of air which was injected into the burner at different pressures for any definite air-shutter adjustment was also determined. This was accomplished by first operating the burner normally, with the top of the box removed, and observing carefully the orifice pressure and the pressure in the burner as indicated on the very sensitive slope U gauge. The lid was then placed on the box and the air passed through a meter into the box at a rate which exactly duplicated the previous condition of pressure within the burner. It is evident that since the gas rate in each case was the same, the volume of air injected into the burner in each case must have been the same. The primary air-gas ratio for gas pressures of 0.25, 0.5, 1, 2, 3, 4, and 5 inches was thus obtained.

Before beginning a test the gas was lighted long enough for the burner to be heated to its normal temperature. All tests herein reported, therefore, were obtained with the "burner hot."

5. METHOD OF GAS ANALYSIS.

An Orsat type of gas analysis apparatus was used for analyzing the various gases used in the tests, also for the determination of the amount of carbon dioxide and oxygen in the products of combustion as sampled above the burner. The apparatus as used is shown in Figure 7.

Mercury was used as the confining liquid in the gas measuring burette. By means of the method of compensation all volume measurements were made at a temperature and pressure that are constant for any analysis. The absorbable constituents were

removed by using the following reagents in the several pipettes: (1) Sodium hydroxide solution for the removal of carbon dioxide (CO_2); (2) fuming sulphuric acid for the removal of the illuminants; (3) alkaline pyrogallol solution for the removal of oxygen (O_2); and (4) acid cuprous chloride for the removal of carbon monoxide (CO).

The amounts of hydrogen (H_2) and methane (CH_4) were determined by the slow combustion method. The amount of ethane (C_2H_6) present in the gases was not determined separately, but the amount being small the error introduced by including it with the percentages of hydrogen and methane present may be ignored.

6. APPARATUS AND METHOD USED FOR ANALYZING PRODUCTS OF COMBUSTION FOR CARBON MONOXIDE.

The amount of carbon monoxide (CO) present in the products of combustion is important as a criterion of the completeness of combustion and of the safe and efficient operation of a burner. A careful analysis of the products of combustion for carbon monoxide was made using the apparatus shown in Figure 8. The general arrangement of apparatus is practically the same as that used by Larson and White, who did considerable work on the quantitative determination of carbon monoxide while in the Chemical Warfare Service. The method is based on the reaction of carbon monoxide (CO) and iodine pentoxide (I_2O_5), which results in the liberation of iodine and the formation of carbon dioxide ($I_2O_5 + 5CO = I_2 + 5CO_2$). The liberated iodine is absorbed in potassium iodide (10 per cent solution) and the amount is determined by titration with carefully standardized sodium thiosulphate ($Na_2S_2O_3$). Since the amount of liberated iodine and the volume of sample passed through the apparatus is known, the amount of carbon monoxide in the products of combustion as sampled can be calculated.

In order to get a result that is comparable with that for any other burner, the products of combustion are analyzed for content of carbon dioxide and oxygen by means of the Orsat apparatus. The amount of oxygen in the sample is directly related to the air present, namely, where x = amount of oxygen in the sample, and since normal air contains 20.93 per cent oxygen by volume, then

$$\frac{20.93 - x}{20.93} = \text{per cent of products of combustion free from air.}$$

Using this factor we can calculate the per cent of carbon monoxide and carbon dioxide on the air-free basis. The calculation of the

carbon monoxide produced in cubic feet per hour is made as follows:

Let a = per cent of CO (air-free basis).
b = per cent of CO_2 (air-free basis).
C = CO_2 produced by combustion of 1 foot^3 of gas.
R = rate at which gas is burned in cubic feet per hour
then

$$\frac{a}{a+b} \times C \times R = \text{cubic feet of carbon monoxide produced per hour.}$$

Referring to Figure 8, the path of travel of the sample of the products of combustion will be traced as the sample is drawn through the apparatus by suction, connection for which is made at 18. The sample of the products of combustion is contained in the sampling tube (1) and is displaced by means of water. As the water rises in the sampling tube (1) and displaces the sample it ultimately acts on the float valve (2) which automatically cuts off the flow of water and allows the purging with air to begin. The sample passes through absorption towers filled with glass beads containing, respectively, chromic acid (3), sodium hydroxide (4), and concentrated sulphuric acid (5). The absorption tower containing chromic acid is heated to approximately 212° F by means of a steam jacket. The hot chromic acid will remove any illuminants, should there be any present; while the sodium hydroxide will remove the carbon dioxide (CO_2) and the sulphuric acid will absorb most of the moisture. The U-tube (6) contains stick sodium hydroxide (NaOH) and acts as a guard tube for the absorption tower of sulphuric acid and it also will remove any trace of carbon dioxide that might still be in the sample. The next U-tube (7) contains phosphorous pentoxide (P_2O_5) where the last trace of moisture is removed. The unit marked "8" is an oil bath in which is mounted a U-tube containing alternate layers of iodine pentoxide and glass wool. The bath is heated by an electric immersion type heater (11) to a temperature of 310° F. (155° C.) and a uniform temperature is maintained by means of a stirring motor (12). The liberated iodine is absorbed in a potassium-iodide solution contained in a Gomberg bulb (9). The Gomberg absorption bulb is attached by ground-glass joints so that it can be easily removed and the iodine solution rinsed into a flask for titration with standardized sodium-thiosulphate solution. The air used in purging passes through an absorption tower containing concentrated sulphuric acid (14), and a U-tube filled with

activated charcoal for the removal of any carbon monoxide that might be in the room atmosphere. The mercury trap (16) acts as a seal when the sample is drawn into the apparatus and also prevents dust in the charcoal from being carried over by the air used in purging. The electric heater and stirring motor are controlled by means of a rheostat and lamps mounted on the switchboard (17) at the extreme left.

The method used in sampling the products of combustion is fully described in "Carbon monoxide in the products of combustion fron natural gas burners," by I. V. Brumbaugh and G. W. Jones. Figure 9 shows the apparatus used.

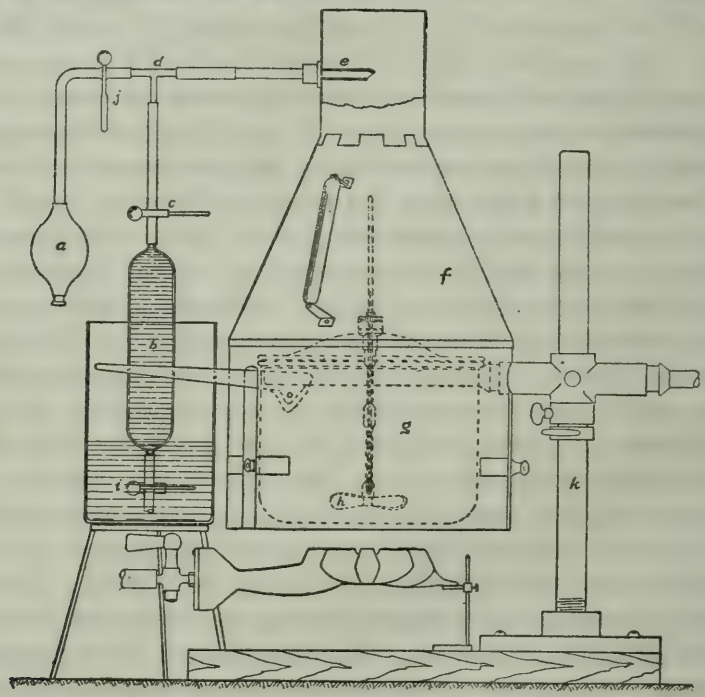

FIG. 9.—*Apparatus used for sampling products of combustion.*

IV. TIME REQUIRED AND CUBIC FEET OF GAS USED TO HEAT 2 QUARTS (4.17 LBS.) OF WATER TO BOILING, CALCULATED EFFICIENCY OF HEATING, AND THE CONDITION OF GOOD ADJUSTMENT FOR TWO TYPES OF BURNERS.

It has been often said that laboratory tests are made with such high degree of accuracy and refinement in adjustment that the application of the results to actual practice is very difficult. Every effort was made in this series of efficiency tests of gases of

10 different heating values to make the condition of test as practical as possible. The tests of each gas were made on each of the ranges shown in Figures 3 and 4. The burners were adjusted in the way that a practical gas fitter would adjust the appliance in a consumer's home.

In Baltimore the pressure of the gas when supplied at the consumers' appliances averages about 3 inches. The initial adjustment of the burners for each kind of gas was made for that pressure. After the careful initial adjustment no other changes were made in the gas orifice or air shutter when the burner was operated at other pressures.

To make a good adjustment the gas-line pressure was first set for 3 inches; then the orifice was so reamed (if necessary) and the air shutter so set that a flame was obtained which was distinctly blue, with a pronounced blue inner cone. The type of flame with good adjustment of gas and primary air might be described as a "normal flame." The flame was neither "hard and stiff" nor "soft and flimsy."

In this connection the reader must bear in mind that when a burner is adjusted for the right kind of flame at a pressure of 3 inches and the pressure is then reduced to 1 inch or increased to 5 inches, *the type of flame is not visibly altered but the rate of flow of gas and, therefore, the size of the flame with each pressure is decidedly different.*

Complaints of poor service are often made when the gas pressure is adequate and the capacity of the service pipe is sufficient, but the orifice on the appliance is too small to deliver the desired amount of gas. On the other hand, complaints arise when the demand for gas is greater than the capacity of the service pipes. It is almost impossible to maintain an absolutely uniform pressure at all times, and tests of efficiency with each kind of gas were made, therefore, when gas was supplied at pressures of 1, 2, 3, 4, and 5 inches. The results obtained are plotted on the curves of the various figures and are marked "efficiency," where efficiency in per cent is plotted as the ordinate with gas-line pressure in inches of water as the abscissa.

The time required to heat the water (2 quarts) from initial temperature to boiling was noted in each case. The time required to heat from 80° F. to boiling was then calculated. These are the time values shown in the tables and are the same as those which have been plotted and are labeled "Time required to heat 2 quarts of water to boiling."

From the amount of gas used and the time required for a test the gas rate in cubic feet per hour was determined. The results are shown in the tables and also in the various figures by the curves marked "Rate, cubic feet per hour."

The above procedure was followed and the results plotted in a similar manner with each of 10 different gases.

After the efficiency tests of each kind of gas had been completed, the burner with the same gas cock and orifice was connected to the burner-testing apparatus without changing the adjustment of the air shutter. With this apparatus the amount of primary air injected into the burner by the gas, with the air shutter set for "good adjustment," was determined at pressures ranging from 0.25 inch to 5 inches. These values are shown by the curves marked "Primary air-gas ratio obtained with good adjustment."

If too much primary air is injected into a burner, the flames will blow from the ports or flash back. From previous experience of the bureau in work for commissions and municipalities it may be stated that when operating burners under these conditions the public will complain of "air in the gas," "poor gas," and popping of burners. The burners were operated with each kind of gas under varying gas rates and the amount of air determined which would cause the flames to just leave the ports or to flash back into the burner at each gas rate. The dashed line labeled "flames blow from ports" and "flash back" show at what rate of consumption and ratios of primary air to gas this complaint could occur with the different gases. It will be observed that the curve showing the condition of good adjustment for each kind of gas falls well below the curves for "flash back" and "flames blow from ports."

Since the velocity of combustion varies with the composition of the gas, and the velocity of the mixture through the ports varies with the port area of the burner, the ratios at which the "flash back" and "blow from ports" conditions occur will vary with the kind of gas, the heating value, the rate of consumption, and the type of burner.

If only a certain ratio of air to gas is admitted into the burner with the gas, a yellow-tipped flame will result. The values of the air-gas ratios at which this condition occurs are shown for the different kinds of gases by the curves marked "Yellow tip appears at this ratio." Such a flame will generally blacken the utensil and is likely to liberate poisonous products. The housewife strenuously objects to a flame that blackens utensils.

The amount of air required for the complete combustion of 1 foot^3 of gas is calculated from the analysis of the gas and is indicated by a dashed line marked "Ratio required for complete combustion" on the figures that follow. The average height of the flame and the blue inner cones were measured at the time of each efficiency test. The average height of the flame is very difficult to determine and the values shown in the tables are only approximate. The height of the blue inner cone is very definite and easily measured.

1. TESTS OF "500" B. T. U. CITY GAS (MIXED COKE-OVEN AND WATER GAS).

(*a*) BURNER NO. 1.

The pressure was set at 3 inches; then the size of the gas orifice and the opening of the air shutter of the burner were adjusted to obtain the type of flame which appliance fitters consider will give the best service. With this adjustment the air shutter was about 20 per cent open. Without changing the burner adjustments, efficiency tests were made at pressures of 1, 2, 3, 4, and 5 inches.

In Table 2 are given the rate of consumption in cubic feet per hour, B. t. u. per cubic foot, B. t. u. delivered per hour, cone and flame height, minutes required to heat 2 quarts of water from 80° F. to boiling, the cubic feet of gas used, and the efficiency obtained at the above five pressures. The values of efficiency, rate of consumption in cubic feet per hour, and the time required to heat 2 quarts (4.17 pounds) of water from 80° F. to boiling are plotted in Figure 10.

The burner, with the same gas cock, orifice, and air-shutter adjustment, was connected to the burner-testing apparatus to determine how much of the air required for combustion entered the burner through the air-shutter opening. The air-injection tests are plotted in Figure 11 and connected by solid lines and labeled "Primary air-gas ratio obtained with good adjustment." Let us consider the case when the burner was operated at a pressure of 3 inches and the gas rate was 22.7 feet^3/hr. The test showed that 52.2 feet^3 of air per hour were injected into the burner. The ratio of primary air to gas was 52.2 divided by 22.7, which equals 2.3. This is the value plotted on the curve and marked "3 in." The other points of the curve show the ratios obtained at other pressures.

From the analysis of city gas given in Table 1 it was computed that the oxygen from 4.26 feet^3 of air is required to completely

burn a cubic foot of the gas. This value is shown by the dashed line of Figure 11 labeled "Ratio required for complete combustion."

Referring again to the rate of consumption at 3 inches pressure, the total air required for complete combusion was $22.7 \times 4.26 = 96.7$ feet^3 of air per hour, or $96.7 - 52.2 = 44.5$ feet^3 of air per hour supplied as secondary air.

It will be noted in Figure 11 that the burner will not flash back under any condition when the gas rate exceeds 6 feet^3/hr. Beyond this rate the flames will leave the port when the air-gas ratio is high enough to make the velocity of the mixture through the ports greater than the velocity of combustion. The ratio at which the flames leave the ports is plotted for varying gas rates in the curve marked "Flames blow from ports" in Figure 11.

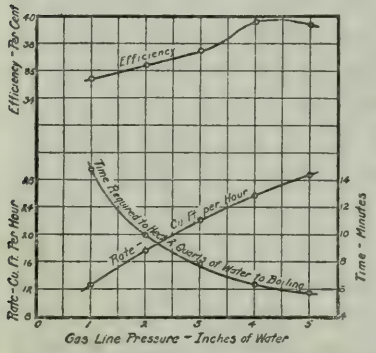

FIG. 10.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with city gas of 492 B. t. u. and burner No. 1.*

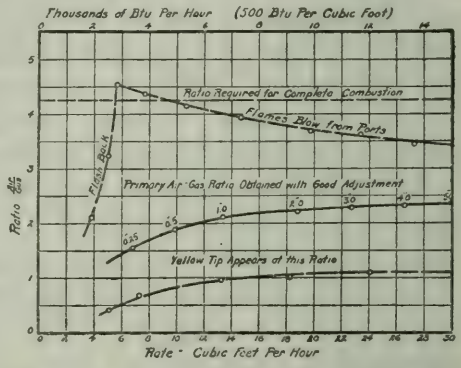

FIG. 11.—*Primary air-gas ratio obtained with city gas of 495 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.628.

The reader will observe in Figure 11 that the air-gas ratio at the good adjustment with any gas rate is well below that at which the "flames blow from ports" or the "flash back" occurs and is well above the ratio at which yellow tips appear at the top of the blue inner cone.

TABLE 1.—Average Analysis of "500" B. t. u. City Gas[1] Used in Tests.

CO_2	per cent	4.1
Illuminants	do	6.5
O_2	do	.8
CO	do	21.5
CH_4	do	16.2
H_2	do	36.6
N_2	do	14.3
Specific gravity		.619
Noncombustibles	per cent	19.2

[1] City gas consisted of approximately one-third coke-oven gas and two-thirds water gas.

TABLE 2.—"500" B. t. u. City Gas, 0.618 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	12.74	491	6,255	0.28	0.70	14.88	3.16	35.5
2	17.95	497	8,920	.38	.94	10.13	3.03	36.5
3	22.48	491	11,040	.44	1.16	7.97	2.98	37.6
4	25.95	491	12,740	.50	1.35	6.52	2.82	39.8
5	29.08	491	14,270	.55	1.45	5.85	2.84	39.6

(*b*) BURNER NO. 2.

The same orifice that was used with Burner No. 1 to test "500" B. t. u. city gas was connected to Burner No. 2. The air shutter was then completely closed to make the good adjustment. It should be noted that the mixer of Burner No. 2 (see Fig. 2) is a separate casting into which the injecting or mixer tube makes a loose fit, the slot for the set screw of the air shutter is uncovered when the shutter is closed, and the air-shutter cap is not tight

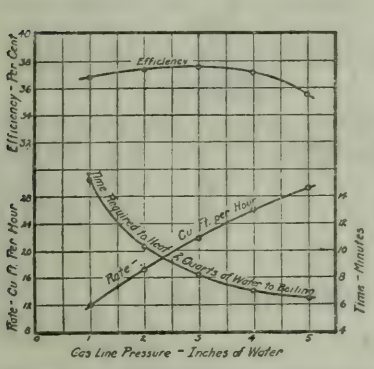

FIG. 12.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with city gas of 492 B. t. u. and burner No. 2.*

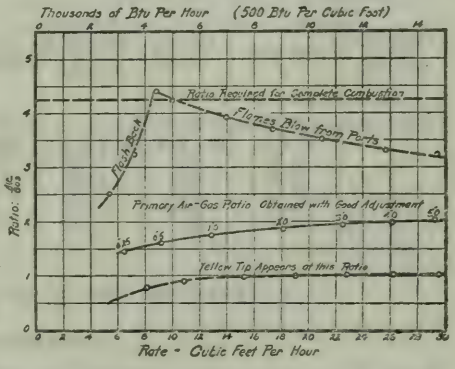

FIG. 13.—*Primary air-gas ratio obtained with city gas of 495 B. t. u. and burner No. 2 a the different conditions of operation.*

Specific gravity of gas, 0.628.

against the mixer face. These openings alone allowed a sufficient amount of primary air to enter the burner at the good adjustment.

The efficiency values, etc., are given in Table 3. If one will compare the results of the tests of city gas obtained with Burner No. 2 with those of Burner No. 1, it will be noted that there is no appreciable difference. This is due primarily to the fact that both burners were the same distance from utensil (1⅜ inches) and the

type of flame with each was approximately the same as shown by the cone heights given in Tables 2 and 3. Since the same orifice was used when testing with each burner the same gas rates are obtained at corresponding pressures, and since the efficiency in each case is approximately the same, it follows that there should be no appreciable difference in the time required to heat a given amount of water to boiling at a given pressure. The curves of Figures 10 and 12 verify this since they are almost identical.

The operation tests of Burner No. 2 are shown by Figure 13. The location of the curves are very similar to those of Figure 11, showing the test of Burner No. 1. The curve showing the "primary air-gas ratio obtained with good adjustment" is a little lower than that for Burner No. 1. Those who made the adjustment believed they had exactly duplicated the flame used in the tests of Burner No. 1, but there is some question whether the eye can detect any less variation in the type of flame.

TABLE 3.—"500" B. t. u. City Gas, 0.624 Specific Gravity—Burner No. 3, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	11.94	495	5,860	0.31	0.64	15.22	3.03	36.7
2	17.27	492	8,500	.37	.70	10.32	3.00	37.3
3	21.45	492	10,550	.40	.85	8.23	2.98	37.5
4	25.92	492	12,750	.48	1.40	6.98	3.02	37.1
5	29.20	492	14,370	.50	1.50	6.44	3.14	35.5

2. TESTS OF "450" B. T. U. COKE-OVEN GAS.

(*a*) BURNER NO. 1.

With coke-oven gas it was found that the same orifice and air-shutter adjustment as made for the city gas was correct for good adjustment. The fact that no readjustment was necessary may be accounted for by the increase in the rate of gas consumption (due to the lower specific gravity) compensating for the drop in heating value. In other words, the hourly rate of B. t. u. supplied to the burner changed but little and the momentum of the gas (which governs the primary air injection) remained approximately the same with the result that the appearance of the flame was not visibily altered.

The average analysis of the gas used in this test is given in Table 4. Table 5 and Figures 14 and 15 require no detailed explanation for the reader familiar with the preceding discussion.

The adjustment of the air shutter of Burner No. 1 for the "450" B. t. u. coke-oven gas was such as to give an air opening approximately 20 per cent of the area of the air inlet.

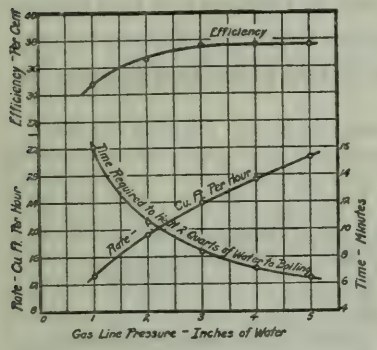

FIG. 14.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with coke-oven gas of 447 B. t. u. and burner No. 1.*

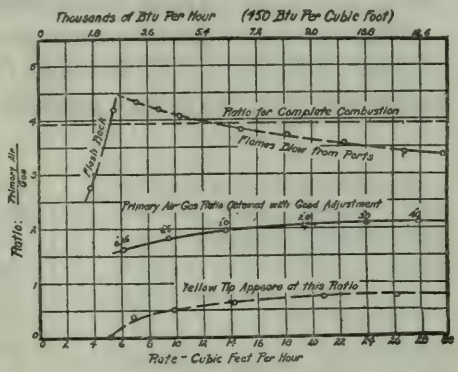

FIG. 15.—*Primary air-gas ratio obtained with coke-oven gas of 447 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.55.

TABLE 4.—Average Analysis of "450" B. t. u. Coke-Oven Gas as Received from Sparrows Point, Md.

CO_2	per cent	3.2
Illuminants	do	3.0
O_2	do	1.0
CO	do	9.6
CH_4	do	22.8
H_2	do	41.5
N_2	do	18.9
Specific gravity		.54
Noncombustibles	per cent	23.1

TABLE 5.—"450" B. t. u. Coke-Oven Gas, 0.55 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft./hr.[3]	B. t. u./ft.[3]	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.[3]	Per cent.
1	13.25	447	5,930	0.27	0.65	16.14	3.54	34.8
2	19.11	447	8,520	.35	.80	10.54	3.36	36.7
3	23.80	447	10,650	.43	.93	8.34	3.27	37.6
4	27.25	447	12,180	.48	1.12	7.21	3.27	37.6
5	30.50	447	13,640	.50	1.32	6.43	3.27	37.6

(*b*) BURNER NO. 2.

The same orifice and air-shutter adjustment of this burner as used in the test of city gas was also correct for coke-oven gas of this heating value. The reason for this is explained in the discussion of the Burner No. 1 when operated with coke-oven gas. Although the air shutter was completely closed, the burner received the required primary air through the openings of the loose fittings.

The analysis of the coke-oven gas used in the tests of this burner is given in Table 4. Table 6 and Figures 16 and 17 should be self-explanatory to the reader familiar with the preceding discussion.

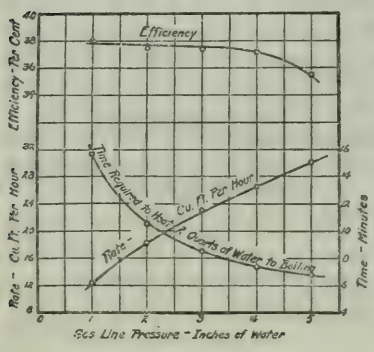

FIG. 16.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with coke-oven gas of 453 B. t. u. and burner No. 2.*

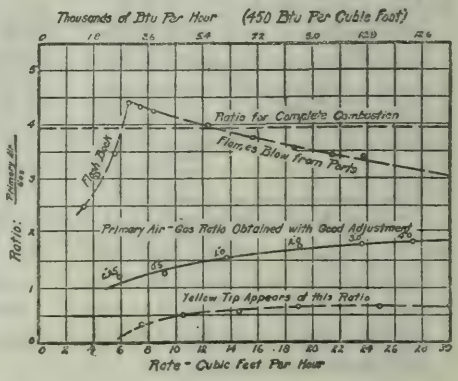

FIG. 17.—*Primary air-gas ratio obtained with coke-oven gas of 447 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.55.

TABLE 6.—"450" B. t. u. Coke-Oven Gas, 0.54 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	12.18	453	5,530	0.30	0.55	15.71	3.19	38.1
2	18.44	453	8,360	.38	.77	10.55	3.23	37.5
3	22.90	453	10,380	.45	.90	8.48	3.24	37.4
4	26.62	453	12,070	.50	1.07	7.36	3.27	37.2
5	30.20	453	13,690	.53	1.23	6.80	3.42	35.5

3. TESTS OF "525" B. T. U. COAL GAS.

(*a*) BURNER NO. 1.

The coal gas used in these tests was obtained from the Philadelphia Gas Works. The gas was received in cylinders compressed to a pressure of approximately 150 atmospheres, which probably

caused some of the illuminants to condense. It would seem that the average analysis given in Table 7 is, therefore, very similar to what should be expected if the gas were scrubbed for light oils.

To make the good adjustment of this burner it was necessary to have the air shutter about three-fourths open.

The results of the efficiency and operation tests of Burner No. 1 are given in Table 8 and Figures 18 and 19.

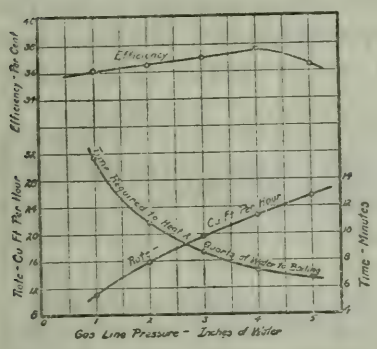

FIG. 18.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with coal gas of 523 B. t. u. and burner No. 1.*

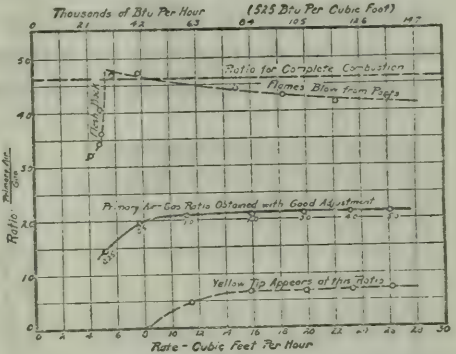

FIG. 19.—*Primary air-gas ratio obtained with coal gas of 523 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.44.

TABLE 7.—Average Analysis of "525" B. t. u. Coal Gas Received from the Philadelphia Gas Works.

CO_2	per cent..	2.0
Illuminants	do....	3.3
O_2	do....	.8
CO	do....	8.2
CH_4	do....	28.9
H_2	do....	49.3
N_2	do....	7.5
Specific gravity		.444
Noncombustibles	per cent..	10.3

TABLE 8.—"525" B. t. u. Coal Gas, 0.444 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	11.09	523	5,800	0.27	0.60	15.75	2.91	36.1
2	15.85	523	8,290	.34	.80	10.87	2.88	36.5
3	19.75	523	10,330	.40	1.05	8.63	2.84	37.0
4	22.78	523	11,900	.44	1.20	7.32	2.78	37.7
5	25.70	523	13,440	.48	1.30	6.74	2.89	36.4

(*b*) BURNER NO. 2.

The air shutter was about one-half open for the good adjustment of Burner No. 2 with this gas. This gas required the largest air-shutter opening for the condition of good adjustment of any of the gases tested. This is due to the low specific gravity, which was 0.44. The heating value of this coal gas is nearly the same as that of the city gas, and the gas rate would be nearly the same to give a uniform B. t. u. rate per hour. But the specific gravity of the coal gas is much less than that of city gas, and hence the amount of air that can be injected per cubic foot of gas is less. Therefore, it was necessary to open the air shutter to a greater

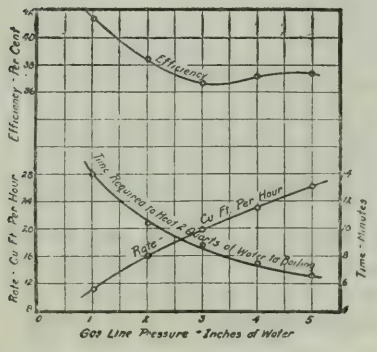

FIG. 20.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with coal gas of 524 B. t. u. and burner No. 2.*

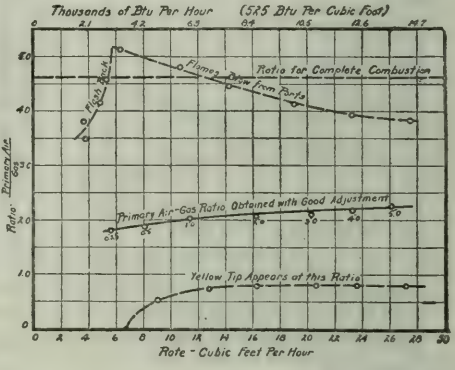

FIG. 21.—*Primary air-gas ratio obtained with coal gas of 524 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.44.

extent in order to draw more primary air into the burner to obtain the same good adjustment.

The average analysis of the "525" B. t. u. coal gas is reported in Table 7.

The efficiency and operation tests of this burner are given in Table 9 and Figures 20 and 21.

TABLE 9.—"525" B. t. u. Coal Gas, 0.444 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	10.91	524	5,720	0.32	0.70	13.94	2.53	41.4
2	15.83	524	8,290	.37	1.00	10.31	2.73	38.4
3	19.73	524	10,340	.42	1.20	8.77	2.86	36.7
4	22.89	524	12,000	.50	1.30	7.41	2.82	37.2
5	26.03	524	13,650	.53	1.50	6.48	2.81	37.4

4. TESTS OF "300" B. T. U. WATER GAS.

(a) BURNER NO. 1.

To make the good adjustment of Burner No. 1 with "300" B. t. u. water gas it was necessary to completely close the air shutter and to put a rubber sleeve over the shank of the gas cock to stop the flow of air through the hole in the air shutter. Since "300" B. t. u. water gas burns more rapidly than that of higher heating value, and since the ratio of air to gas required for complete combustion is so much less, the good adjustment occurs with a much lower ratio of primary air to gas. The ratio is about 0.6. Burner No. 1 consumed 33.5 feet ^{3} of gas at the good adjustment for 3 inches pressure and only required 20.1 feet ^{3} of primary air. If one wishes to use "300" B. t. u. water gas with this burner, it is necessary to have a tight-fitting air shutter or to reduce the gas pressure in order to reduce the injection of air into the burner.

The average analysis of the "300" B. t. u. water gas is given in Table 10.

Table 11 and Figures 22 and 23 contain the efficiency and operation data obtained with Burner No. 1.

Figure 23 is very interesting. Burner No. 1 could be made to "flash back" at all rates of consumption at which tests were made. This is the only gas that has given such results with this burner.

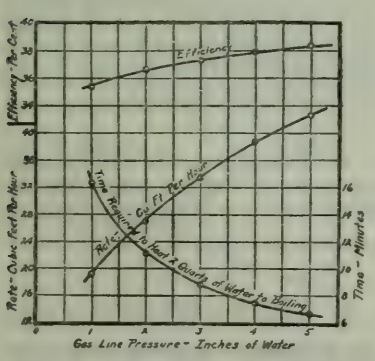

FIG. 22.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 299 B. t. u. and burner No. 1.*

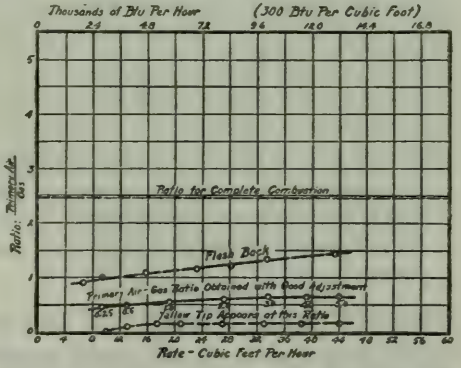

FIG. 23.—*Primary air-gas ratio obtained with water gas of 299 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.574.

TABLE 10.—Average Analysis of "300" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent	8.2
Illuminants	do	1.4
O_2	do	.3
CO	do	34.0
CH_4	do	1.9
H_2	do	50.4
N_2	do	3.8
Specific gravity		.57
Noncombustibles	per cent	12.3

TABLE 11.—"300" B. t. u. Water Gas, 0.574 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	19.16	299	5,730	0.20	0.50	16.29	5.20	35.4
2	26.95	299	8,060	.25	.75	11.17	5.02	36.7
3	33.46	299	10,000	.28	1.00	8.85	4.94	37.3
4	38.90	299	11,630	.32	1.10	7.48	4.85	38.0
5	42.70	299	12,780	.35	1.25	6.75	4.80	38.4

(*b*) BURNER NO. 2.

The good adjustment of Burner No. 2 for "300" B. t. u. water gas was made by closing the opening between the air mixer and the mixing tube with asbestos and by inserting a sheet of copper

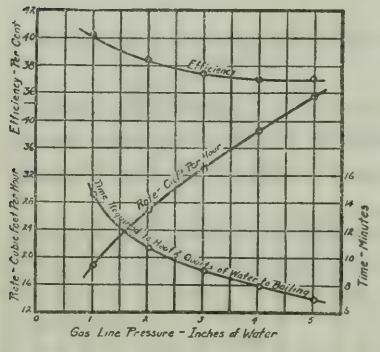

FIG. 24.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 297 B. t. u. and burner No. 2.*

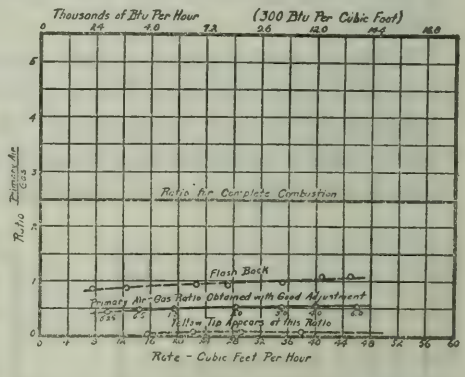

FIG. 25.—*Primary air-gas ratio obtained with water gas of 300 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.566.

between the air-shutter cap and the air mixer. When this was done practically no air could enter the burner. All the required air for the good adjustment entered the burner through a hole about three-sixteenth inch diameter made in the sheet of copper.

The average analysis of the "300" B. t. u. water gas is given in Table 10.

Table 12 and Figures 24 and 25 give the efficiency and complete operation data of burner No. 2 with this gas.

TABLE 12.—"300" B. t. u. Water Gas, 0.566 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	18.82	297	5,590	0.20	0.55	14.65	4.59	40.3
2	26.96	297	8,000	.25	.75	10.69	4.80	38.5
3	32.89	297	9,740	.28	1.00	9.02	4.96	37.5
4	38.36	297	11,390	.32	1.25	7.91	5.04	37.0
5	43.35	297	12,880	.35	1.40	6.90	5.05	37.1

5. TESTS OF "350" B. T. U. WATER GAS.

(a) BURNER NO. 1.

With the "350" B. t. u. water gas it was necessary to have the air shutter closed. Sufficient primary air for good adjustment entered through the opening around the shank of the gas cock and a small opening that was not covered by the cap of the air shutter.

The average analysis of the "350" B. t. u. water gas is given in Table 13.

The efficiency and operation data are found in Table 14 and Figures 26 and 27.

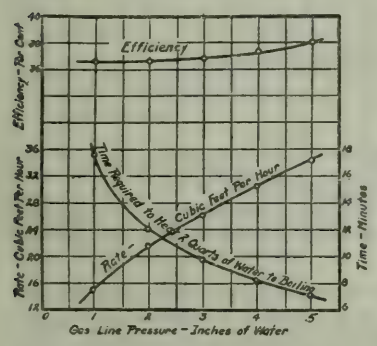

FIG. 26.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 356 B. t. u. and burner No. 1.*

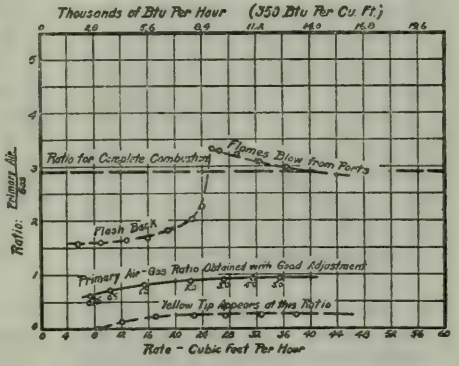

FIG. 27.—*Primary air-gas ratio obtained with water gas of 359 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.583.

TABLE 13.—Average Analysis of "350" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent..	7.4
Illuminants	do....	3.2
O_2	do....	.7
CO	do....	34.1
CH_4	do....	3.7
H_2	do....	48.1
N_2	do....	2.8
Specific gravity		.58
Noncombustibles	per cent..	10.9

TABLE 14.—"350" B. t. u. Water Gas, 0.58 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	14.57	356	5,190	0.22	0.55	17.47	4.25	36.4
2	21.34	356	7,600	.27	.77	11.92	4.24	36.5
3	26.00	356	9,260	.30	1.00	9.72	4.21	36.7
4	30.40	356	10,820	.35	1.20	8.18	4.15	37.3
5	34.33	356	12,230	.40	1.35	7.11	4.07	38.0

(*b*) BURNER NO. 2.

All of the primary air required for the good adjustment of Burner No. 2 with "350" B. t. u. water gas entered through the loose-fitting cap. The slot opening for the air-shutter screw was covered with a piece of sheet copper and the opening where the mixing tube enters the air mixer was closed with asbestos.

The average analysis of the "350" B. t. u. water gas is given in Table 13.

The efficiency and operation data of burner No. 2 are given in Table 15 and Figures 28 and 29.

FIG. 28.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 352 B. t. u. and burner No. 2.*

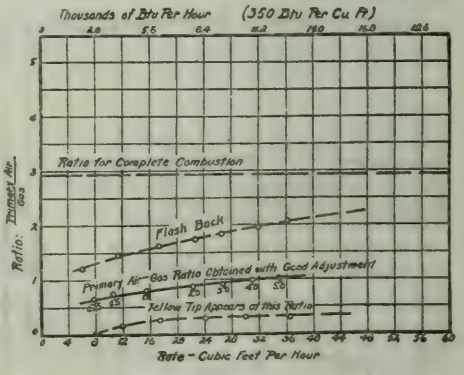

FIG. 29.—*Primary air-gas ratio obtained with water gas of 352 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.576.

TABLE 15.—"350" B. t. u. Water Gas, 0.58 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	13.72	352	4,830	0.25	0.60	17.29	3.95	39.6
2	21.33	352	7,510	.27	.80	11.35	4.04	38.6
3	26.04	352	9,170	.30	1.00	9.60	4.18	37.4
4	30.55	352	10,750	.33	1.15	8.29	4.22	37.2
5	34.46	352	12,130	.36	1.35	7.29	4.18	37.4

6. TESTS OF "400" B. T. U. WATER GAS.

(a) BURNER NO. 1.

To make the good adjustment with this heating value the air shutter was almost closed. The air opening was between 2 and 3 per cent of the maximum.

The average analysis of the "400" B. t. u. water gas is given in Table 16.

Table 17 and Figures 30 and 31 give the efficiency and complete operation data obtained with this burner and "400" B. t. u. water gas.

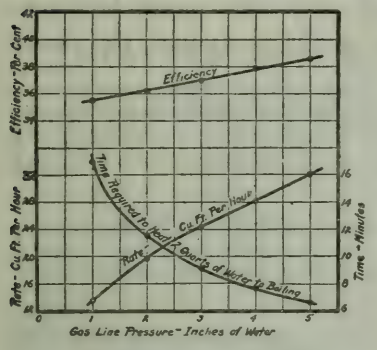

FIG. 30.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 399 B. t. u. and burner No. 1.*

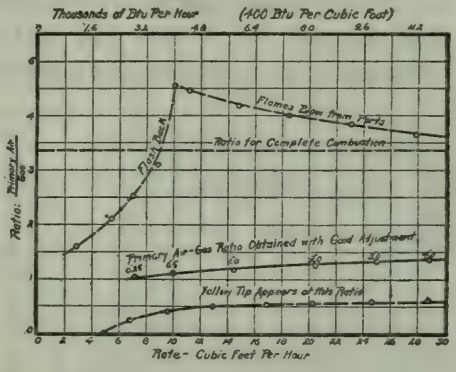

FIG. 31.—*Primary air-gas ratio obtained with water gas of 406 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.585.

TABLE 16.—Average Analysis of "400" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent	6.2
Illuminants	do	4.5
O_2	do	.2
CO	do	33.6
CH_4	do	6.4
H_2	do	43.8
N_2	do	5.3
Specific gravity		.59
Noncombustibles	per cent	11.7

TABLE 17.—"400" B. t. u. Water Gas, 0.595 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	13.60	399	5,420	0.25	0.54	17.01	3.86	35.6
2	19.71	399	7,870	.28	.78	11.61	3.81	36.2
3	24.42	399	9,740	.32	.95	9.19	3.74	37.0
4	28.21	399	11,260	.36	1.15	7.75	3.65	37.9
5	32.17	399	12,840	.40	1.34	6.64	3.57	38.6

(*b*) **BURNER NO. 2.**

This burner can not be operated with this heating value gas when adjusted at a pressure of 3 inches, even with the air shutter completely closed, unless much of the remaining primary air opening is closed. To obtain a good adjustment asbestos was used to completely close the opening where the mixing tube enters the air mixer and also to close about two-thirds of the slot opening for the air-shutter screw.

Interesting information obtained with this burner is shown by the "flash-back" curve given in Figure 33. It will be noted that the "flash-back" curve is entirely different from that obtained with Burner No. 1 (see Fig. 31) and with this same heating-value gas. It is known that the size of the ports and the com-

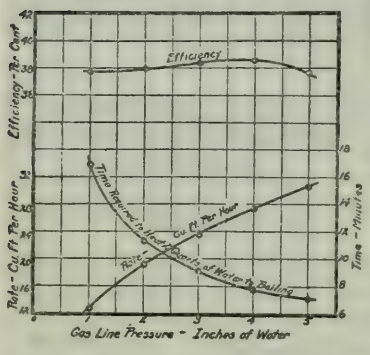

FIG. 32.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 401 B. t. u. and burner No. 2.*

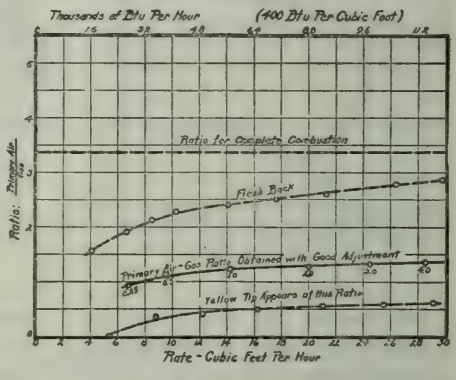

FIG. 33.—*Primary air-gas ratio obtained with water gas of 406 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.585.

position of the gas are factors causing "flash back." Burner No. 2 has several ports larger than No. 40 drill, through which it is believed the flame flashed back under different conditions than those at which the "flash back" would have occurred if the ports were all No. 40 drill size. It would seem that gases of lower heating value tend to disclose such defects. However, these factors do not affect the operation of the burner when properly adjusted.

The average analysis of the "400" B. t. u. water gas is given in Table 16.

Table 18 and Figures 32 and 33 contain the efficiency and complete operation data obtained with this burner and "400" B. t. u. water gas.

TABLE 18.—"400" B. t. u. Water Gas, 0.595 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	12.85	401	5,150	0.23	0.64	16.98	3.64	37.8
2	19.18	401	7,700	.26	.88	11.32	3.62	38.0
3	23.62	401	9,470	.29	.97	9.08	3.58	38.4
4	27.54	401	11,050	.33	1.08	7.76	3.56	38.6
5	30.85	401	12,350	.36	1.25	7.10	3.65	37.7

7. TESTS OF "450" B. T. U. WATER GAS.

(a) BURNER NO. 1.

To test water gas of this heating value with Burner No. 1 the same orifice was used as in the tests of "500" B. t. u. city gas and and "450" B. t. u. coke-oven gas. At 3 inches pressure less heat units were delivered per hour than with the two above gases, but

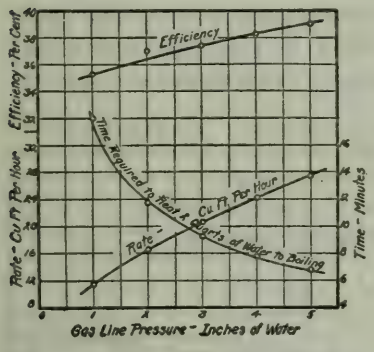

FIG. 34.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 454 B. t. u. and burner No. 1.*

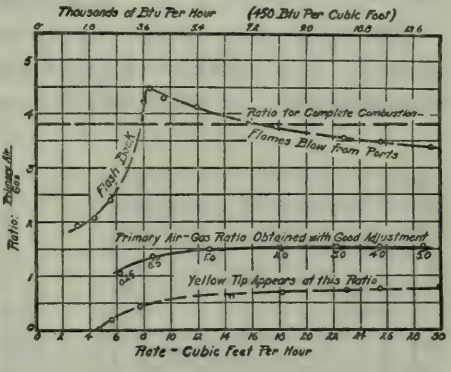

FIG. 35.—*Primary air-gas ratio obtained with water gas of 448 B. t. u. and burner No. 1 at the different conditions of operation.*
Specific gravity of gas, 0.614.

it was decided that the burner still received an ample amount. In order to secure a good flame, however, the air shutter had to be closed until it was about 8 per cent open. The reason for the air-shutter readjustment will be discussed in Section VII of this report.

The average analysis of the "450" B. t. u. water gas is given in Table 19.

Table 20 and Figures 34 and 35 give the efficiency and complete operation data obtained with this burner and "450" B. t. u. water gas.

TABLE 19.—Average Analysis of "450" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent.	5.2
Illuminants	do	5.6
O_2	do	.3
CO	do	29.4
CH_4	do	10.0
H_2	do	42.2
N_2	do	7.3
Specific gravity		.617
Noncombustibles	per cent.	12.8

TABLE 20.—"450" B. t. u. Water Gas, 0.614 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	11.44	454	5,200	0.25	0.55	18.04	3.44	35.3
2	16.71	454	7,590	.30	.78	11.73	3.28	37.0
3	20.75	454	9,420	.35	.90	9.37	3.24	37.4
4	24.30	454	11,040	.40	1.00	7.83	3.17	38.2
5	27.45	454	12,460	.45	1.15	6.80	3.11	39.0

(*b*) BURNER NO. 2.

The air shutter of this burner was completely closed; the same as with "450" coke-oven and "500" B. t. u. city gas, which was approximately 33 per cent coke-oven gas. The flame was harder

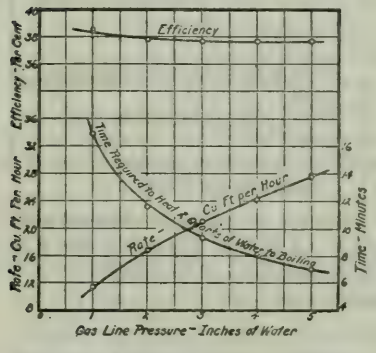

FIG. 36.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 448 B. t. u. and burner No. 2.*

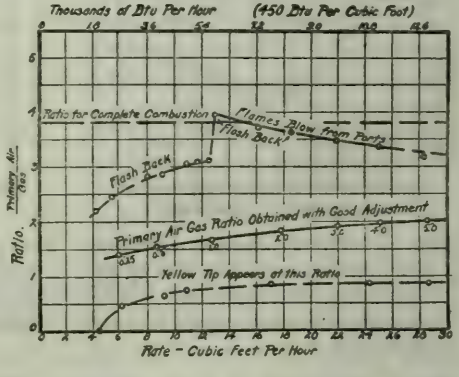

FIG. 37.—*Primary air-gas ratio obtained with water gas of 447 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.620.

than that which we consider to be a good adjustment; but it was impossible to secure the good adjustment without stopping the flow of some of the air that entered the burner through the slot opening for the air-shutter screw or some of that which entered through the loose fitting of the air mixer. It was decided to test the burner without making any further changes, since there was no trouble from flash back when the gas was turned down.

The analysis of the "450" B. t. u. water gas is given in Table 19.

Table 21 and Figures 36 and 37 give the efficiency and complete operation data with this burner.

TABLE 21.—"450" B. t. u. Water Gas, 0.614 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	11.31	448	5,070	0.20	0.50	16.86	3.18	38.6
2	16.78	448	7,520	.25	.75	11.60	3.25	37.8
3	21.13	448	9,470	.28	.85	9.26	3.26	37.7
4	24.12	448	10,810	.30	.95	8.09	3.26	37.7
5	27.70	448	12,400	.34	1.18	7.06	3.26	37.7

8. TESTS OF "500" B. T. U. WATER GAS.

(a) BURNER NO. 1.

To make good adjustment with "500" B. t. u. water gas the air shutter was about 16 per cent open.

The average analysis of the gas is given in Table 22.

Table 23 and Figures 38 and 39 give the efficiency and complete operation data obtained with "500" B. t. u. water gas.

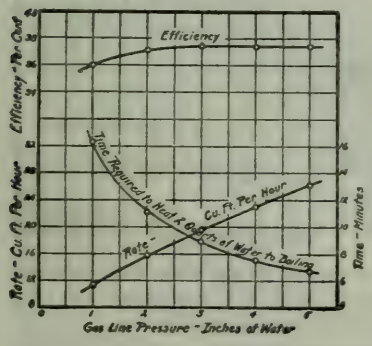

FIG. 38.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 505 B. t. u. and burner No. 1.*

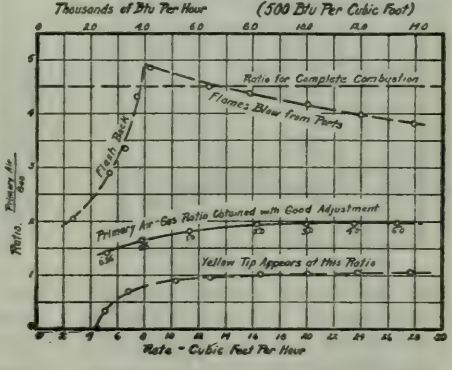

FIG. 39.—*Primary air-gas ratio obtained with water gas of 501 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.633

TABLE 22.—Average Analysis of "500" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent..	5.1
Illuminants	do....	8.5
O_2	do....	.3
CO	do....	32.1
CH_4	do....	11.2
H_2	do....	38.9
N_2	do....	3.9
Specific gravity		.641
Noncombustibles	per cent..	9.3

TABLE 23.—"500" B. t. u. Water Gas, 0.634 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	11.11	505	5,620	0.25	0.50	16.33	3.02	36.0
2	15.82	505	8,000	.30	.75	11.15	2.94	37.1
3	19.60	505	9,900	.35	.90	8.90	2.91	37.4
4	22.86	505	11,540	.40	1.10	7.67	2.91	37.4
5	26.18	505	13,230	.45	1.30	6.67	2.91	37.5

(*b*) BURNER NO. 2.

Completely closing the air shutter allowed a little too much air to enter the burner for the good adjustment and a piece of sheet metal was inserted over the slot for the air-shutter screw which practically closed the opening.

The average analysis of the "500" B. t. u. water gas is given in Table 22.

Table 24 and Figures 40 and 41 contain the efficiency and operation data of this burner with "500" B. t. u. water gas.

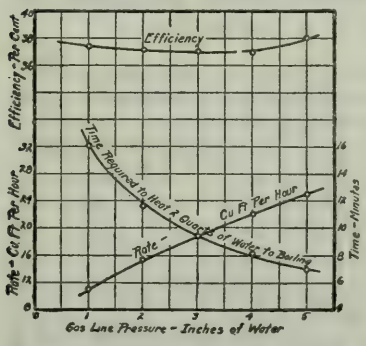

FIG. 40.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 503 B. t. u. and burner No. 2.*

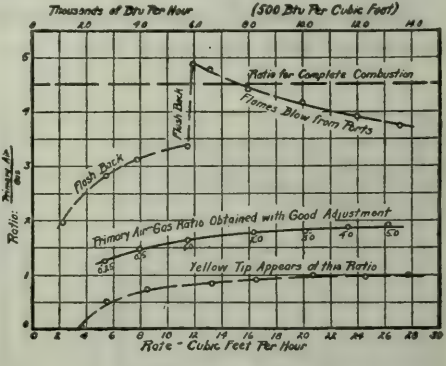

FIG. 41.—*Primary air-gas ratio obtained with water gas of 501 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.633.

TABLE 24.—"500" B. t. u. Water Gas, 0.634 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	10.91	503	5,450	0.26	0.75	16.10	2.93	37.4
2	15.24	503	7,660	.31	.85	11.60	2.95	37.1
3	18.95	503	9,540	.37	1.00	9.45	2.96	37.0
4	21.70	503	10,910	.41	1.10	8.20	2.97	36.9
5	24.98	503	12,560	.45	1.20	6.91	2.88	38.0

9. TESTS OF "550" B. T. U. WATER GAS.

(a) BURNER NO. 1.

The air shutter of Burner No. 1 was about 20 per cent open for the good adjustment with water gas of this heating value. This is the same adjustment that was made for "450" B. t. u. coke-oven and "500" B. t. u. city gas, but the "450" B. t. u. coke-oven gas had a specific gravity of 0.55, the "500" B. t. u. city gas a specific gravity of 0.62, and the "550" water gas a specific gravity of 0.66.

The average analysis of "440" B. t. u. water gas is given in Table 25.

Table 26 and Figures 42 and 43 give the efficiency and complete operation data of Burner No. 1 with "550" B. t. u. water gas.

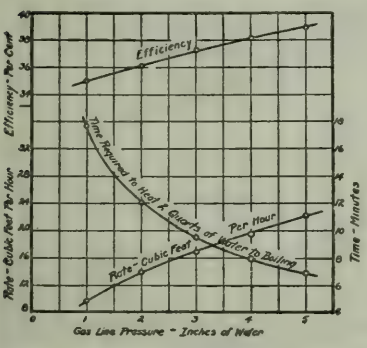

FIG. 42.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 557 B. t. u. and burner No. 1.*

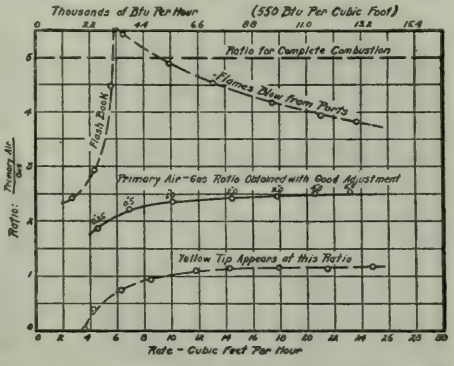

FIG. 43.—*Primary air-gas ratio obtained with water gas of 558 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.662.

TABLE 25.—Average Analysis of "550" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	per cent..	4.2
Illuminants	do....	10.7
O_2	do....	.2
CO	do....	32.0
CH_4	do....	12.7
H_2	do....	35.5
N_2	do....	4.7
Specific gravity		.66
Noncombustibles	per cent..	9.1

TABLE 26.—"550" B. t. u. Water Gas, 0.657 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	9.69	549	5,300	0.25	0.50	17.79	2.87	35.0
2	13.95	549	7,660	.30	.70	12.00	2.78	36.1
3	16.68	557	9,290	.35	.90	9.51	2.64	37.3
4	19.33	557	10,930	.40	1.10	8.05	2.59	38.1
5	22.22	557	12,390	.45	1.30	6.86	2.54	38.9

(*b*) BURNER No. 2.

Completely closing the air shutter still allowed a little too much air to enter the burner. The flame was a little too hard, so a piece of thin sheet metal was inserted between the air-shutter cap and air mixer, and over the slot for the air-shutter screw. This was not the equivalent of closing the slot because the piece of inserted sheet metal did not permit as close a fit between the air-shutter cap and air-shutter mixer as there was before the insertion.

The analysis of the "550" B. t. u. water gas is given in Table 25.

Table 27 and Figures 44 and 45 give the efficiency and operation data obtained with Burner No. 2 and "550" B. t. u. water gas.

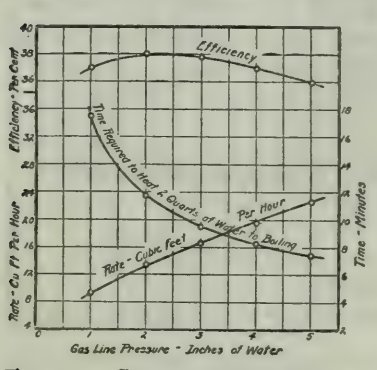

FIG. 44.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 549 B. t. u. and burner No. 2.*

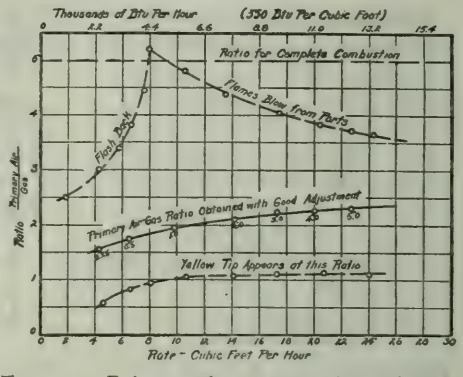

FIG. 45.—*Primary air-gas ratio obtained with water gas of 552 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.662.

TABLE 27.—"550" B. t. u. Water Gas, 0.657 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	9.31	549	5,110	0.25	0.50	17.45	2.71	37.0
2	13.54	549	7,440	.30	.70	11.70	2.64	38.0
3	16.68	549	9,160	.35	.90	9.57	2.66	37.7
4	19.45	549	10,690	.40	1.10	8.30	2.70	37.0
5	22.61	549	12,420	.43	1.28	7.40	2.78	36.0

10. TESTS OF "600" B. T. U. WATER GAS.

(*a*) BURNER No. 1.

The air-shutter setting for the good adjustment of Burner No. 1 was about 50 per cent open. After the tests were in progress it was observed that if one opening of the air shutter was closed by

holding a finger over it the flame was slightly harder than that of the good adjustment. This is contrary to what should be expected when half of the primary air opening is closed after a good adjustment is made. The cause of the irregularity was not thoroughly investigated, but is believed that it was caused by a slight disalignment of the gas stream with the injecting tube of the burner. This matter does not affect our results, but shows the importance of having the gas stream in correct alignment with the injecting tube of the burner where burners are operated with a very low pressure and gas of a high heating value, otherwise sufficient air may not be injected into the burner to secure a good flame.

The average analysis of "600" B. t. u. water gas is given in Table 28.

Table 29 and Figures 46 and 47 give the efficiency and complete operation data of Burner No. 1 with "600" B. t. u. water gas.

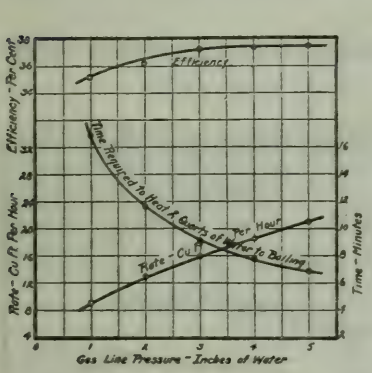

FIG. 46.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 608 B. t. u. and burner No. 1.*

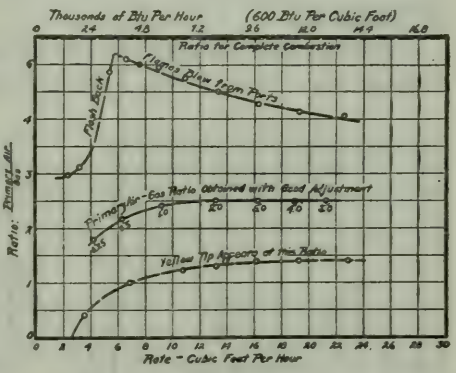

FIG. 47.—*Primary air-gas ratio obtained with water gas of 608 B. t. u. and burner No. 1 at the different conditions of operation.*

Specific gravity of gas, 0.682.

TABLE 28.—Average Analysis of "600" B. t. u. Water Gas Made at Spring Gardens Plant.

CO_2	Per cent..	4.8
Illuminants	do....	12.8
O_2	do....	.3
CO	do....	29.2
CH_4	do....	14.2
H_2	do....	35.0
N_2	do....	3.7
Specific gravity		.676
Noncombustibles	Per cent..	8.8

TABLE 29.—"600" B. t. u. Water Gas, 0.682 Specific Gravity—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	9.17	608	5,500	0.25	0.50	16.85	2.57	35.2
2	12.91	608	7,860	.33	.75	11.77	2.50	36.2
3	15.92	608	9,680	.40	.95	9.14	2.43	37.3
4	18.50	608	11,250	.45	1.15	7.85	2.42	37.4
5	21.03	608	12,800	.50	1.35	6.90	2.42	37.5

(*b*) **BURNER No. 2.**

The air shutter was completely closed for the good adjustment of Burner No. 2 because enough primary air entered the burner through the slot for the air-shutter screw, the loose-fitting shutter, and the opening where the mixing tube enters the air mixer.

The average analysis of the "600" B. t. u. water gas is given in Table 28.

Table 30 and Figures 48 and 49 contain the efficiency and operation data of Burner No. 2 with "600" B. t. u. water gas.

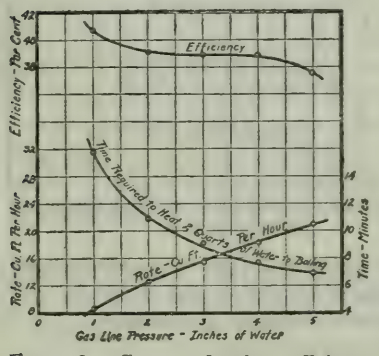

FIG. 48.—*Curves showing efficiency, time required, and cubic feet of gas used to heat 2 quarts of water to boiling with water gas of 608 B. t. u. and burner No. 2.*

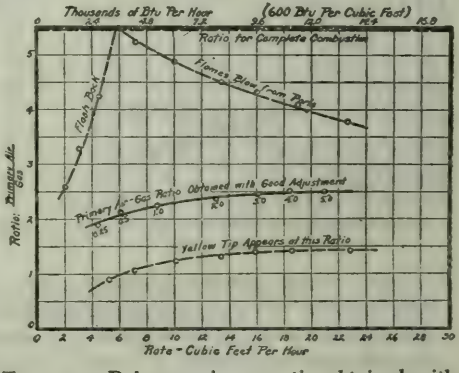

FIG. 49.—*Primary air-gas ratio obtained with water gas of 608 B. t. u. and burner No. 2 at the different conditions of operation.*

Specific gravity of gas, 0.680.

TABLE 30.—"600" B. t. u. Water Gas, 0.680 Specific Gravity—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

Pressure in inches of water.	Gas rate.	Heating value.	Quantity of heat supplied.	Cone height.	Flame height.	Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
	Ft.³/hr.	B. t. u./ft.³	B. t. u./hr.	Inch.	Inches.	Minutes.	Feet.³	Per cent.
1	8.68	608	5,280	0.30	0.60	15.35	2.22	40.7
2	12.80	608	7,780	.35	.80	10.86	2.32	39.0
3	15.40	608	9,360	.40	.95	9.10	2.33	38.9
4	18.18	608	11,050	.45	1.15	7.89	2.33	38.9
5	20.89	608	12,700	.50	1.35	6.91	2.40	37.6

11. TESTS FOR CARBON MONOXIDE IN THE PRODUCTS OF COMBUSTION.

The products of combustion from the preceding tests were analyzed in order to determine whether any carbon monoxide was produced. The analyses show that with the "regular" burners used on gas ranges, when properly adjusted, practically no carbon monoxide was produced with any of the gases tested unless gas was burned at a rate greater than about 12,000 B. t. u./hr. Since gas is seldom burned above this rate with burners of "regular" size the danger from carbon-monoxide poisoning is very remote if the burners are properly adjusted. When gas was burned above this rate, the amount of carbon monoxide produced was such as would cause headaches in a poorly ventilated room.

For the larger top burners, which are commonly designated as "giant" burners, the limitation of 12,000 B. t. u./hr. does not apply, although no tests have been made to determine the maximum safe consumption for these burners.

The heating value of the gas or the kind of gas did not seem to be factors affecting the production of carbon monoxide.

12. SUMMARY OF GAS ANALYSES.

The average analyses of the different gases tested are given in Table 31. To make the theoretical calculations shown at the bottom of the table, it was assumed that the constituents of the illuminants of water gas averaged $C_{2.6}$ $H_{6.6}$, and that the illuminants of coke-oven and coal gas averaged C_2H_5.

TABLE 31.—Average Analyses of Gases Tested at Spring Gardens.

Kind of gas	City gas.[1]	Coke-oven gas.	Coal gas.	Water gas.						
Nominal heating value (B. t. u. per cubic foot)	500	450	525	300	350	400	450	500	550	600
Constituents:										
CO_2 per cent	4.1	3.2	2.0	8.2	7.4	6.2	5.2	5.1	4.2	4.8
Ill. do	6.5	3.0	3.3	1.4	3.2	4.5	5.6	8.5	10.7	12.8
O_2 do	.8	1.0	.8	.3	.7	.2	.3	.3	.2	.3
CO do	21.5	9.6	8.2	34.0	34.1	33.6	29.4	32.1	32.0	29.2
CH_4 do	16.2	22.8	28.9	1.9	3.7	6.4	10.0	11.2	12.7	14.2
H_2 do	36.6	41.5	49.3	50.4	48.1	43.8	42.2	38.9	35.5	35.0
N_2 do	14.3	18.9	7.5	3.8	2.8	5.3	7.3	3.9	4.7	3.7
Heating value (B. t. u. per cubic foot, calorimeter)	496	450	524	298	354	400	451	501	556	603
Specific gravity (air=1.0)	0.619	0.542	0.444	0.570	0.580	0.590	0.617	0.641	0.660	0.676
Noncombustibles per cent	10.2	23.1	10.3	12.3	10.90	11.7	12.8	9.3	9.1	8.8
Required for complete combustion of 1 ft.[3] of gas: O_2 cubic feet	.883	.799	.965	.516	.613	.704	.793	.940	1.094	1.148
Required for complete combustion of 1 ft.[3] of gas: air cubic feet	4.22	3.82	4.61	2.46	2.93	3.36	3.79	4.49	4.99	5.47
Cubic feet CO_2 produced by combustion: per cubic foot of gas	.587	.416	.457	.477	.535	.579	.591	.705	.767	.815
Cubic feet CO_2 produced by combustion: per 1,000 B. t. u.	1.48	.925	.872	1.60	1.51	1.45	1.31	1.41	1.38	1.35
Cubic feet water vapor produced by combustion: per cubic foot of gas	.905	.946	1.15	.588	.661	.715	.807	.894	.962	1.06
Cubic feet water vapor produced by combustion: per 1,000 B. t. u.	1.83	2.10	2.20	1.97	1.87	1.79	1.79	1.79	1.73	1.76

[1] City gas contained approximately one-third coke-oven gas and two-thirds water gas.

13. COMPARISON OF RESULTS WITH GASES OF DIFFERENT HEATING VALUES.

1. Within the range of gas consumption normally used in top-burner cooking there will be some variations in the efficiency with the rate of heating. Since this is the case, it appears logical that for an exact comparison of the efficiencies of gases of different heating values the burners must be supplied with the same total quantity of heat units per hour.

2. From observations made by the bureau during service investigations in a large number of cities and from laboratory tests made at the bureau it has been observed that a good average adjustment on a regular burner will represent a consumption of about 9,000 B. t. u./hr. An adjustment for this rate will allow a variation in gas pressure which will be within the usual legal requirements without causing poor service or loss in efficiency. For an example, a burner adjusted to 9,000 B. t. u. at 3 inches pressure will consume 7,000 B. t. u. at 1.8 inches and will not exceed 11,000 B. t. u. at 4.4 inches pressure.

TABLE 32.—Summary of Tests for Rate of Consumption of 7,000 B. t. u. per Hour—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³	B. t. u./ft.³		Ft.³/hr.			Minutes.	Foot.³	Per cent.
500	492	0.618	14.23	2.15	156	13.2	3.12	35.8
			COKE-OVEN GAS.					
450	447	0.55	15.66	2.0	149	13.3	3.46	35.6
			COAL GAS.					
525	523	0.444	13.38	2.10	169	13.0	2.90	36.3
			WATER GAS.					
300	299	0.574	23.40	0.58	189	13.1	5.10	36.1
350	356	.583	19.65	.88	189	13.0	4.25	36.4
400	399	.595	17.54	1.26	177	13.1	3.83	36.0
450	454	.614	15.42	1.52	180	13.0	3.33	36.4
500	505	.634	13.86	1.90	179	12.9	2.97	36.6
550	557	.657	12.57	2.40	164	13.2	2.77	35.7
600	608	.682	11.51	2.47	175	13.2	2.53	35.8

TABLE 33.—Summary of Tests for Rate of Consumption of 9,000 B. t. u. per Hour—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³	B. t. u./ft.³		Ft.³/hr.			Minutes.	Foot.³	Per cent.
500	492	0.618	18.30	2.23	153	10.0	3.05	36.6
				COKE-OVEN GAS.				
450	447	0.55	20.12	2.06	146	9.9	3.33	36.9
				COAL GAS.				
525	523	0.444	17.20	2.10	169	10.0	2.86	36.7
				WATER GAS.				
300	299	0.574	30.10	0.61	186	9.9	4.97	37.0
350	356	.583	25.28	.92	185	10.0	4.21	36.7
400	399	.595	22.55	1.32	172	10.0	3.75	36.7
450	454	.614	19.81	1.53	180	9.9	3.26	37.2
500	505	.634	17.83	1.95	171	9.8	2.86	37.3
550	557	.657	16.16	2.45	161	9.9	2.66	37.1
600	608	.682	14.80	2.48	175	10.0	2.46	36.8

TABLE 34.—Summary of Tests for Rate of Consumption of 11,000 B. t. u. per Hour—Burner No. 1, 48 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³	B. t. u./ft.³		Ft.³/hr.			Minutes.	Feet.³	Per cent.
500	492	0.618	22.35	2.28	150	7.9	2.94	38.0
				COKE-OVEN GAS.				
450	447	0.55	24.60	2.10	144	8.0	3.27	37.6
				COAL GAS.				
525	523	0.444	21.03	2.12	168	8.0	2.82	37.3
				WATER GAS.				
300	299	0.574	36.80	0.63	184	8.0	4.88	37.7
350	356	.583	30.90	.95	183	8.0	4.13	37.4
400	399	.595	27.57	1.36	169	8.0	3.67	37.6
450	454	.614	24.22	1.54	179	7.9	3.17	38.2
500	505	.634	21.78	1.96	171	8.0	2.91	37.4
550	557	.657	19.75	2.48	160	7.9	2.58	38.2
600	608	.682	18.09	2.48	177	8.0	2.42	37.4

(a) RESULTS WITH BURNER NO. 1.

The results of tests of the gases of various heating values with Burner No. 1 for rates of consumption of 7,000, 9,000, and 11,000 B. t. u./hr. are shown in Tables 32, 33, and 34, respectively.

Values of efficiency obtained with the various heating values, the corresponding rates of consumption in cubic feet per hour, and the time required to heat 2 quarts of water to boiling from 80° F., as given in Table 33 (9,000 B. t. u./hr.), have been plotted in Figure 50. The tests proved conclusively that when the regular burner No. 1, which is placed 1⅜ inches from the utensil, consumed gas

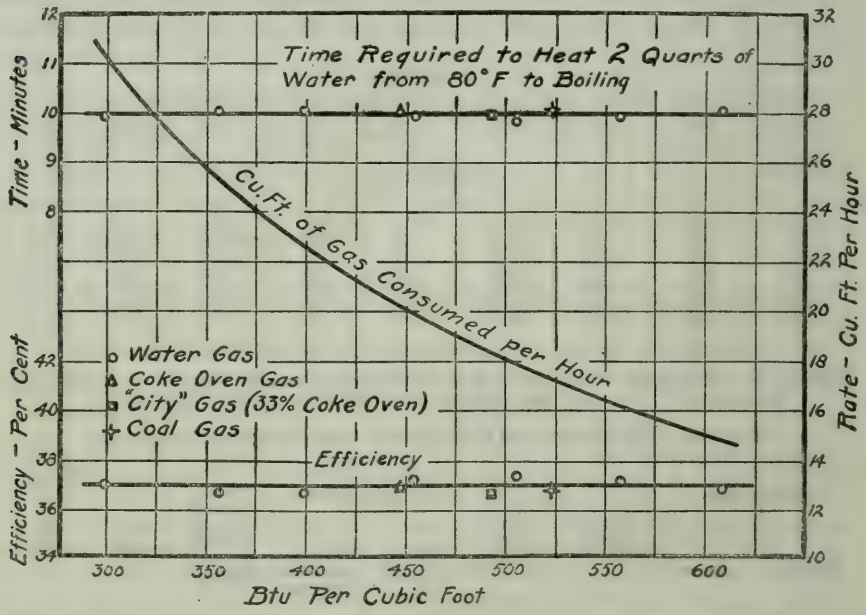

FIG. 50.—*Curves showing efficiency, rate of consumption, and time required to heat 2 quarts of water from 80° F. to boiling when burner No. 1 is operated at 9,000 B. t. u. per hour with gases of various heating values.*

at the rate of 9,000 B. t. u./hr., all the different gases, irrespective of the kind of gas or B. t. u. content per cubic foot, gave a constant efficiency of about 37 per cent, at least within the range of heating values used in these tests (300 to 600 B. t. u.). The time required to heat 2 quarts of water to boiling from 80° F. with 9,000 B. t. u./hr. was about 10 minutes.

At a rate of 7,000 B. t. u./hr. an average efficiency of about 36 per cent was obtained (see Table 32), and about 13 minutes were required to heat 2 quarts of water to boiling from 80° F. For a rate of 11,000 B. t. u./hr. the average efficiency was about 37.7 per cent (see Table 34), and the time required to heat 2 quarts of

water to boiling from 80° F. was about 8 minutes. These results show that the efficiency of heat absorption varies only slightly with a change in the rate of heat supply. It follows, therefore, that the rate of heating varies almost directly with the rate of supply of heat.

(*b*) RESULTS WITH BURNER NO. 2.

The efficiencies obtained with the gases of different heating value when Burner No. 2 was used are very similar to those obtained with Burner No. 1. Both burners were 1⅜ inches from top of

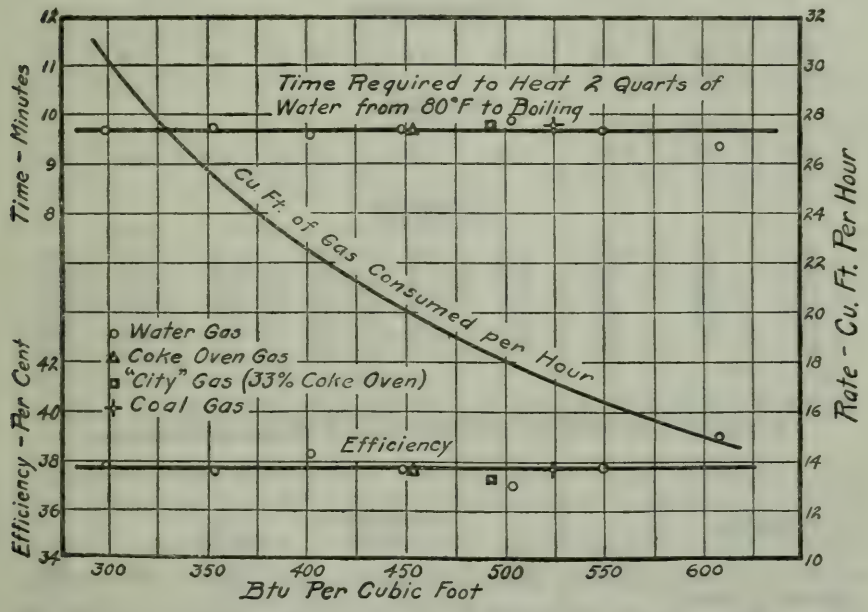

FIG. 51.—*Curves showing efficiency, rate of consumption, and time required to heat 2 quarts of water from 80° F. to boiling when burner No. 2 is operated at 9,000 B. t. u. per hour with gases of various heating values.*

grid (bottom of utensil), but Burner No. 2 has four ports less than No. 1 and is 3⅝ inches in diameter, while No. 1 is 4¼ inches in diameter.

Tables 35, 36, and 37, for rates of consumption of 7,000, 9,000, and 11,000 B. t. u./hr., respectively, show the efficiencies and operation data obtained with the gases of different heating values with this burner. Values from Table 36 (9,000 B. t. u./hr.) have been plotted in Figure 51. The results show that with gases of different heating value and a consumption of 9,000 B. t. u./hr. an average efficiency of about 37.8 per cent was obtained and the time required to heat 2 quarts of water to boiling from 80° F. was about 9.7 minutes.

TABLE 35.—Summary of Tests for Rate of Consumption of 7,000 B. t. u. per Hour—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³ 500	B. t. u./ft.³ 492	0.624	Ft.³/hr. 14.22	1.81	175	Minutes. 12.8	Feet.³ 3.02	Per cent. 37.0
				COKE-OVEN GAS.				
450	453	0.54	15.45	1.61	173	12.5	3.22	37.7
				COAL GAS.				
525	524	0.444	13.25	2.05	172	11.8	2.63	39.9
				WATER GAS.				
300	297	0.566	23.57	0.51	197	12.1	4.74	39.1
350	352	.576	19.88	.84	191	12.2	4.05	38.6
400	401	.595	17.45	1.27	177	12.5	3.62	37.9
450	448	.614	15.63	1.77	162	12.4	3.23	38.0
500	503	.634	13.91	1.73	184	12.7	2.94	37.2
550	549	.657	12.75	2.08	178	12.5	2.64	37.9
600	608	.680	11.51	2.37	181	12.0	2.30	39.4

TABLE 36.—Summary of Tests for Rate of Consumption of 9,000 B. t. u. per Hour—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³ 500	B. t. u./ft.³ 492	0.624	Ft.³/hr. 18.30	1.87	171	Minutes. 9.8	Feet.³ 3.00	Per cent. 37.3
				COKE-OVEN GAS.				
450	453	0.54	19.86	1.73	166	9.7	3.22	37.7
				COAL GAS.				
525	524	0.444	17.16	2.12	168	9.7	2.78	37.8
				WATER GAS.				
300	297	0.566	30.30	0.52	195	9.7	4.89	37.9
350	352	.576	25.58	.90	185	9.8	4.15	37.6
400	401	.595	22.44	1.30	174	9.6	3.58	38.3
450	448	.614	20.10	1.87	156	9.7	3.26	37.7
500	503	.634	17.89	1.81	179	9.9	2.95	37.0
550	549	.657	16.40	2.18	173	9.7	2.65	37.8
600	608	.680	14.80	2.45	176	9.4	2.33	38.9

TABLE 37.—Summary of Tests for Rate of Consumption of 11,000 B. t. u. per Hour—Burner No. 2, 44 Ports, No. 40 Drill—Utensil 1 3/8 Inches from Burner.

CITY GAS (ONE-THIRD COKE-OVEN GAS, TWO-THIRDS WATER GAS).

Heating value.		Specific gravity (air=1).	Gas rate (actual).	Good adjustment of burner.		Time required to heat 2 quarts of water from 80 to 212° F.	Gas used.	Efficiency.
Nominal.	Actual.			Primary air-gas ratio.	B. t. u. per cubic foot of mixture.			
B. t. u./ft.³	B. t. u./ft.³		Ft.³/hr.			Minutes.	Feet.³	Per cent.
500	492	0.624	22.35	1.90	170	8.0	2.98	37.5
				COKE-OVEN GAS.				
450	453	0.540	24.28	1.81	161	8.0	3.24	37.5
				COAL GAS.				
525	524	0.444	21.0	2.18	165	8.2	2.86	36.7
				WATER GAS.				
300	297	0.566	37.03	0.53	194	8.1	4.99	37.1
350	352	.576	31.25	.99	177	8.1	4.21	37.1
400	401	.595	27.42	1.35	171	7.8	3.55	38.6
450	448	.614	24.54	1.94	153	8.0	3.26	37.6
500	503	.634	21.86	1.85	176	8.1	2.96	36.9
550	549	.657	20.03	2.27	168	8.1	2.72	36.9
600	608	.680	18.08	2.48	175	7.7	2.32	38.9

(c) EFFECT OF ROOM TEMPERATURE ON EFFICIENCY TESTS.

Some investigators claim that in order to get consistent and reproducible results in the efficiency values it is necessary to have a very constant room temperature. In these tests it was impossible to control the room temperature, but in making a study of the efficiency results and the room temperature at the time of the tests, it is impossible to find any indication that the variation in temperature affected the results.

Table 38 shows average room temperatures during the time that each series of efficiency tests were made.

TABLE 38.—Average Room Temperatures During Efficiency Tests.

Kind of gas.....	Water gas.							City gas.	Coke-oven gas.	Coal gas.
Nominal heating value (B. t. u. per cubic foot).	300	350	400	450	500	550	600	500	450	525
Room temperature:										
Burner No. 1.....	82	86	94	98	83	87	82	80	84	75
Burner No. 2.....	79	86	99	92	79	88	83	89	85	77

14. ADJUSTMENT OF BURNERS FOR GASES OF DIFFERENT HEATING VALUE AND SPECIFIC GRAVITY.

The different factors that enter into the proper adjustment of a burner are (1) heating value of the gas; (2) quantity of heat required; (3) kind of gas; (4) gas pressure; (5) specific gravity; and (6) type of air mixer, air shutter, injecting tube, and size of orifice.

The heating value determines the volume of gas that must be supplied the burner. A change of heating value changes the ratio of primary air to gas required for a good flame, and generally necessitates a change of size of orifice and the position of the air shutter.

The kind of gas affects the ease of operation of a burner. Coal and coke oven gas are less susceptible to flash back than water gas, which means that the range of adjustment for good operation is greater than with water gas.

The volume of air injected into a burner is dependent upon the energy of the gas stream, which varies with the volume consumed, the pressure, and the specific gravity of the gas. A change of any one of these factors may necessitate a change of the orifice and the air-shutter position.

The range of heating value to which the burners can be adjusted will depend upon the pressure of the gas, the design of air mixer, air shutter, and injecting tube. There are a few burners of obsolete design in service which do not have an adjustable air shutter and it is more difficult to make adjustments for low heating value gases with such burners.

(*a*) ADJUSTMENT OF BURNER NO. 1.

The adjustment of Burner No. 1 to consume gases of different heating values warrants the conclusion that the burner can be used without alteration to give good service with water gas of a heating value as low as 350 B. t. u./ft.[3] The adjustment for each of the different heating values was made when the pressure was 3 inches. This burner is representative of the "star" type. Star burners are most widely used.

(*b*) ADJUSTMENT OF BURNER NO. 2.

Burner No. 2, which was tested, and which is shown in Figure 2, is one of the older designs and is of the "disk" type. On account of its loose fitting air mixer and air shutter it could not be used with water gas of a heating value lower than about 450 B. t. u. and a pressure of 3 inches without devising some means to obstruct the flow of primary air into the burner.

V. GAS PRESSURE NECESSARY FOR GOOD ADJUSTMENT OF BURNER NO. 1 WITH "500" AND "600" B. T. U. WATER GAS.

When the air shutter of a burner must be partly or almost completely closed to obtain a "good adjustment" it indicates that the burner could be operated equally as well at a lower pressure by using a larger orifice and a larger opening of the air shutter. It is interesting to know what is the minimum pressure required to produce a good flame when the air shutter is in the wide-open position.

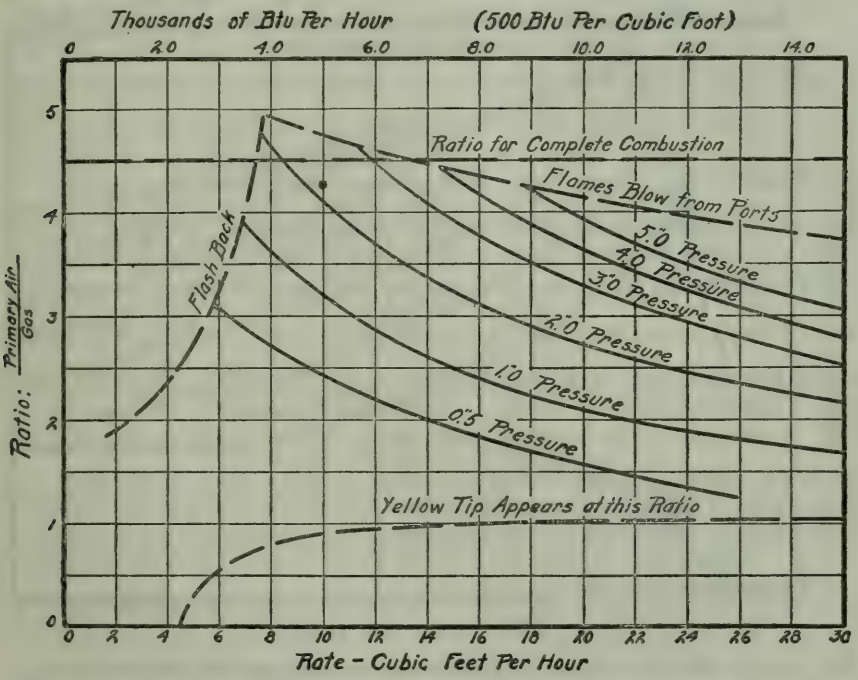

FIG. 52.—*Air-gas ratios obtained at different pressures and gas rates with burner No. 1 when operated with water gas of 501 B. t. u.*

Specific gravity of gas, 0.633. Air shutter wide open.

The required pressure will vary with (1) the design of injecting tube of burner, (2) the type of orifice (fixed orifices require less pressure than adjustable orifices), (3) the specific gravity of the gas, and (4) the heating value of the gas.

TEST NO. 1.—Conditions of test: (1) Air shutter wide open, (2) specific gravity of gas 0.633, (3) water gas, 501 B. t. u./ft.^{3}, and (4) fixed orifices (sharp-edge type).

Figure 52 shows the ratios of air to gas that were obtained with different rates of consumption and pressures of 0.5, 1, 2, 3, 4, and

5 inches when the air shutter was wide open. Orifices of different sizes were used in order to determine these curves. This figure shows that when the gas pressure is constant and the gas rate is changed by changing the size of the orifice, the air-gas ratio decreases as the gas rate increases. Thus the minimum pressure required to produce the proper air-gas ratio is the pressure that will give a good adjustment at the maximum rate at which the burner is to be operated. If 10,000 heat units per hour are taken as the correct consumption for a regular burner, the gas rate

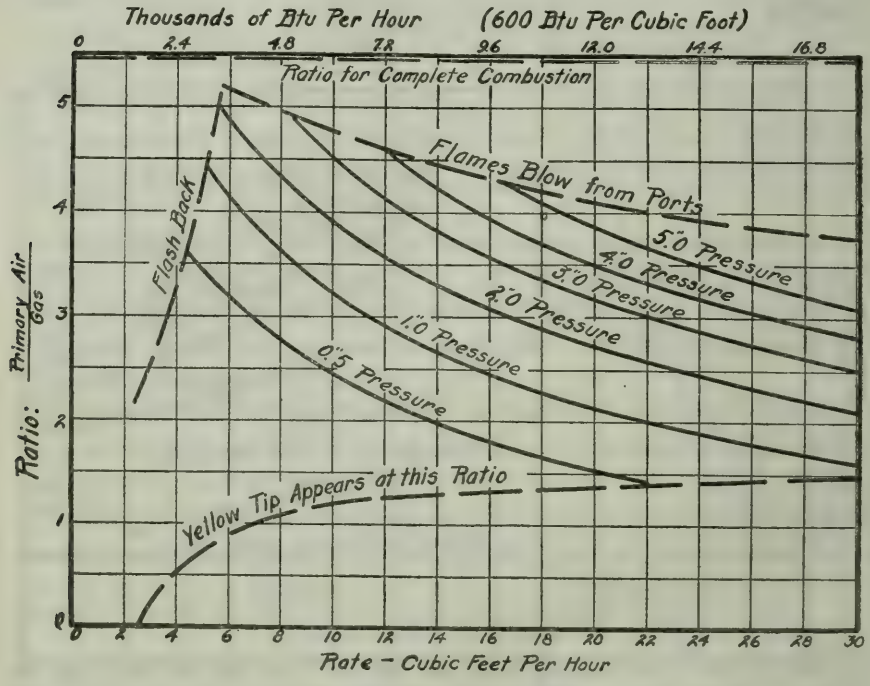

FIG. 53.—*Air-gas ratios obtained at different pressures and gas rates with burner No. 1 when operated with water gas of 608 B. t. u.*

Specific gravity of gas, 0.682. Air shutter wide open.

with 500 B. t. u. gas will be 20 ft.^{3}/hr. From Figure 39, the tests of which were made with 500 B. t. u. water gas, it will be noted that the "good adjustment" at this rate is secured with an air-gas ratio of 1.95. Figure 52 shows that when the air shutter is wide open a pressure of about seventh-eighth inch will produce this air-gas ratio at a gas rate of 20 ft.^{3}/hr. A pressure of 1 inch, therefore, is sufficient to inject the proper amount of air when the burner is supplied with not more than 10,000 B. t. u./hr.

It follows that Burner No. 1, if operated with water gas of 0.63 specific gravity and "500" B. t. u./ft.^{3}, would not need an ad-

justment of the air shutter if the pressure at the orifice were 1 inch. If one wishes to operate the burners now in use with a pressure of 1 inch, it would be necessary to increase the size of orifice and open the air shutter to obtain a good flame.

TEST NO. 2.—Conditions of test: (1) Air shutter wide open, (2) specific gravity of gas 0.682, (3) water gas—608 B. t. u./ft.^{3}, and (4) fixed orifices (sharp-edged type).

The results of this test are shown by Figure 53. The curves of this figure must be compared with the "good adjustment" curve of Figure 47 which was made with the same gas. Figure 47 shows that an air-gas ratio of 2.5 corresponds to a "good adjustment" with "600" B. t. u. water gas. Figure 53 shows that if the air shutter had been wide open, a pressure of about 1¼ inches would have produced the same good adjustment for a consumption of 10,000 B. t. u./hr. (16.7 ft.^{3}).

No tests of this kind were made with Burner No. 2 because it could not be conveniently tested with our equipment. It is believed that an allowance of about one-fourth inch more pressure should be made for Burner No. 2 on account of the design of the injecting tube.

VI. EFFECT OF CHANGE IN HEATING VALUE ON THE FLAME CHARACTERISTICS AND OPERATION OF BURNERS.

1. COMPARISON OF AIR-GAS RATIO AND B. T. U. PER CUBIC FOOT OF MIXTURE WITH WATER GAS OF 400, 500, AND 600 B. T. U. AND COAL GAS OF 525 B. T. U. AT THE UPPER WORKABLE LIMIT, GOOD ADJUSTMENT, AND CONDITIONS AT WHICH YELLOW TIP APPEARS.

The effect of gases of different heating values on the operation of a burner is best shown by curves. Figures 54, 55, 56, and 57 show the data obtained with water gas of 400, 500, and 600 B. t. u. and coal gas of 525 B. t. u. The curves labeled "Flash back," "Flames blow from ports," "Primary air-gas ratio obtained with good adjustment," and "Yellow tip appears at this ratio" have been discussed in a previous section of this report. However, it is well to mention here that the air-gas ratio varies for each particular curve, depending on the heating value of gas used and that there is a slight increase in the range of adjustment (from "yellow tip" to "upper limit of workable adjustment") as the heating value of water gas increases. The curves marked "Upper limit of workable adjustment," were obtained when the air shutter was so adjusted that an explosion did not occur when the gas was turned off from the "on full" position of the gas cock, except when

the gas cock was turned off very suddenly. A burner that is adjusted so that such an explosion will occur as the gas is turned off is very likely to flash back when operated at the rates of consumption used for simmering purposes.

The volume of air required to burn a cubic foot of gas increases as the heating value of the gas increases. This is shown by the curves

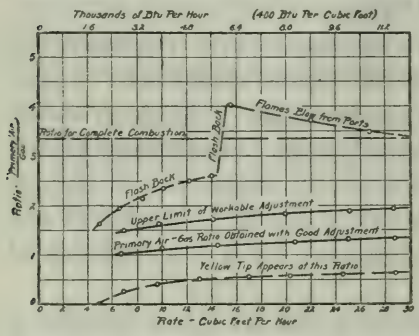

FIG. 54.—*Range of air-gas ratios over which burner No. 1 can be operated with water gas of 400 B. t. u.*

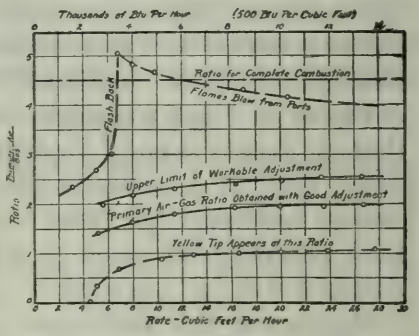

FIG. 55.—*Range of air-gas ratios over which burner No. 1 can be operated with water gas of 500 B. t. u.*

marked "Ratio for complete combustion." A cubic foot of 400 B. t. u. water gas requires the oxygen from about 3.36 feet ^{3} of air for complete combustion; 500 B. t. u. water gas requires about 4.49 feet ^{3} of air; 600 B. t. u. water gas about 5.47 feet ^{3} of air, and 525 B. t. u. coal gas requires about 4.61 feet ^{3} of air.

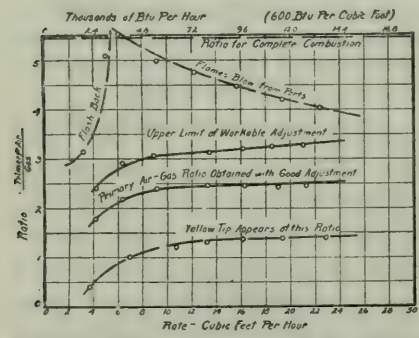

FIG. 56.—*Range of air-gas ratios over which burner No. 1 can be operated with water gas of 600 B. t. u.*

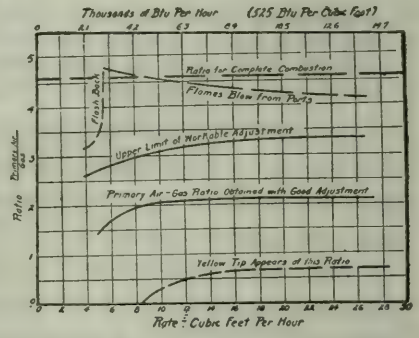

FIG. 57.—*Range of air-gas ratios over which burner No. 1 can be operated with coal gas of 525 B. t. u.*

The burner must be supplied with heat units at the same rate with gases of different heating values to maintain the same service. The comparison of the operation of a burner with gases of different heating value has, therefore, been made when the burner consumed the same number of heat units per hour with each gas. In making this comparison it must be remembered that the volume

of gas required to maintain a constant rate of heat units decreases as the heating value of the gas increases, and that the ratio of air to gas required to burn the gas increases as the heating value increases. To compare the operation of a burner with different gases, then, the mixture of the primary air and gas in the burner must be stated in the same terms for each gas. The B. t. u. content of a cubic foot of the air-gas mixture in the burner at the different adjustments offers the best means of comparison. The B. t. u. per cubic foot of mixture at any adjustment is determined from the gas rate and the air-gas ratio. A comparison of the air-gas ratio and B. t. u. per cubic foot of mixture obtained with Burner No. 1 with 400, 500, and 600 B. t. u. water gas and 525 B. t. u. coal gas is shown in Table 39. The air-gas ratio values are taken from Figures 54, 55, 56, and 57, which show the ratios obtained with the different gases for air-shutter adjustments which gave the same type of flame. The calculations in Table 39 of the B. t. u. per cubic foot of mixture at the various adjustments were made as follows (from Figure 54, with air shutter set for good adjustment):

B. t. u. per cubic foot 400
Rate, B. t. u. per hour 7,000
Rate, cubic feet per hour $\frac{7,000}{400}=17.5$
Air-gas ratio 1.23
Rate of air injection per hour $(17.5\times1.23)=21.5$ ft.^{3}
Total rate per hour (mixture) $(17.5+21.5)=39.0$ ft.^{3}
B. t. u. per cubic foot of mixture, $\frac{7,000}{39.0}=180.$

A study of the calculations given in Table 39 shows that the B. t. u. per cubic foot of mixture at the upper limit of workable adjustment is a constant of about 140 to 145 B. t. u. for water gas of 400, 500, and 600 B. t. u./ft.^{3} This means that there would be no appreciable difference in the use of these three gases with burners adjusted in this manner. A very hard flame is obtained in each case.

The range of workable adjustments of a burner with coal gas is greater than with water gas. It is known that the same care does not have to be exercised when adjusting burners for coal gas as with water gas because the trouble from flash back is not so great. The calculations of the B. t. u. per cubic foot of mixture at the upper workable limit show that 525 B. t. u. coal gas can be satisfactorily burned if the air shutter is adjusted so that the B. t. u. per cubic foot of mixture is as low as about 120. It is interesting to note that when the air shutter was set for the good

adjustment approximately the same B. t. u. per cubic foot of mixture was obtained with these four gases. The average is between 170 and 175 B. t. u./ft.^{3} of mixture. At the adjustment where the yellow tip appears 400, 500, and 600 B. t. u. water gas gave about 250 to 260 B. t. u./ft.^{3} of mixture, while 525 B. t. u. coal gas showed a B. t. u. per cubic foot of mixture of 310 to 330. It should be expected, therefore, that fewer complaints of poor service would be experienced with burners consuming coal gas than with those burning water gas because the yellow flame occurs at a higher B. t. u. per cubic foot of mixture and the upper workable limit at a lower B. t. u. per cubic foot of mixture than with water gas.

TABLE 39.—A Comparison of Air-Gas Ratio and B. t. u. per Cubic Foot of Mixture Obtained with Burner No. 1 and 400, 500, and 600 B. t. u. Water Gas and 525 B. t. u. Coal Gas (Values Taken from Figs. 54, 55, 56, and 57).

Heating value (B. t. u. per cubic foot).	Ratio of air to gas required for complete combustion.	Gas rate.	Very hard flame. Upper workable limit of primary air to gas.		Normal flame. Good adjustment of primary air to gas.		Very soft flame. Yellow tip appears at this condition.	
			Air-gas ratio.	B. t. u. per cubic foot of mixture.	Air-gas ratio.	B. t. u. per cubic foot of mixture.	Air-gas ratio.	B. t. u. per cubic foot of mixture.
		Ft.^{3}/hr.						
RATE, 7,000 B. T. U./HR.								
400	3.36	17.5	1.80	143	1.23	180	0.55	258
500	4.49	14.0	2.37	148	1.85	176	.97	254
600	5.47	11.7	3.13	145	2.46	173	1.30	261
525	4.61	13.3	3.25	124	2.11	169	.58	333
RATE, 9,000 B. T. U./HR.								
400	3.36	22.5	1.87	139	1.28	175	0.58	253
500	4.49	18.0	2.45	145	1.92	171	1.00	250
600	5.47	15.0	3.19	143	2.48	172	1.35	255
525	4.61	17.1	3.33	122	2.14	168	.69	312
RATE, 11,000 B. T. U./HR.								
400	3.36	27.5	1.92	137	1.35	170	0.61	248
500	4.49	22.0	2.50	143	1.95	170	1.00	246
600	5.47	18.3	3.25	141	2.48	172	1.38	252
525	4.61	20.9	3.38	120	2.14	168	.70	310

2. FLAME AND CONE HEIGHTS AT DIFFERENT BURNER ADJUSTMENTS WITH 400, 500, AND 600 B.T.U. WATER GAS.

The flame and cone heights vary with the heating value of the gas.—The curves, Figures 58, 59, and 60, show that with the same adjustment 600 B. t. u. water gas has a higher cone and flame height than 400 B. t. u. water gas. This means that water gas of the lower heating value burns more rapidly than gas of higher heating value.

The gas rate (B. t. u. per hour) affects the cone and flame height.—Cone and flame heights taken from Figures 58, 59, and 60 for rates of consumption of 7,000, 9,000, and 11,000 B. t. u./hr. show clearly that as the rate is increased the cone and flame heights are increased for any particular adjustment.

The cone and flame heights vary with the air-gas ratio.—The tests have shown that over the range of adjustments at which a burner can be satisfactorily operated the flame height continually decreases as the ratio of primary air to gas is increased from that which produces the yellow tip to that where the flames blow from ports. The cone height decreases in like manner until the point

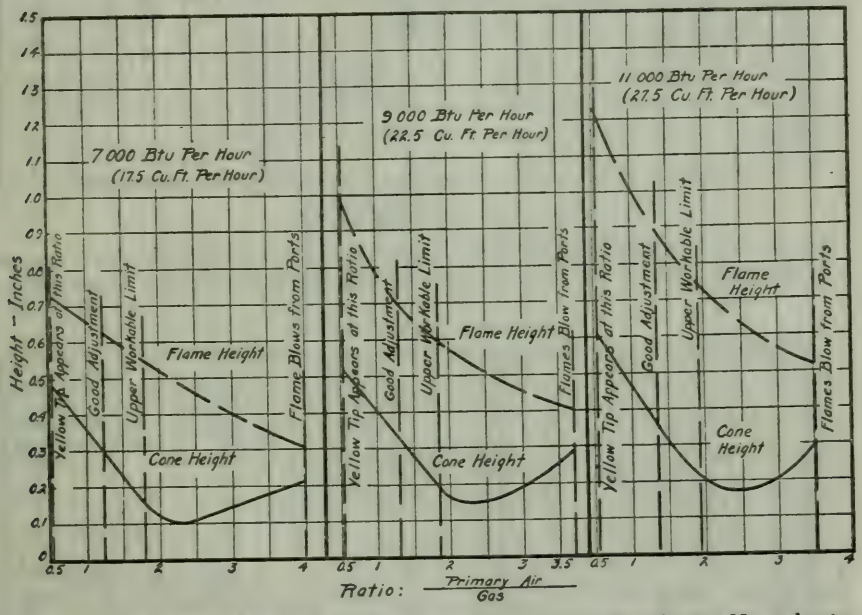

FIG. 58.—*Cone and flame heights with varying air-gas ratios when burner No. 1 is operated with 400 B. t. u. water gas at rates of 7,000, 9,000, and 11,000 B. t. u. per hour.*

where the flames blow from ports is nearly reached, when the cones begin to increase in height. This is more pronounced with water gas of 400 B. t. u. (see Fig. 58) than with water gas of higher heating value. (See Figs. 59 and 60.) The surface of the cone marks the beginning of combustion, and the height of the cone therefore depends on the ratio of the mixture, the velocity of the mixture, and the rate of combustion of the gas for the different mixtures. When the air-gas ratio is increased from a low value the increase in the velocity of combustion is at first greater than the increase of the velocity of the mixture through the ports, and the height of the cone, which is formed by gas which has not yet begun to

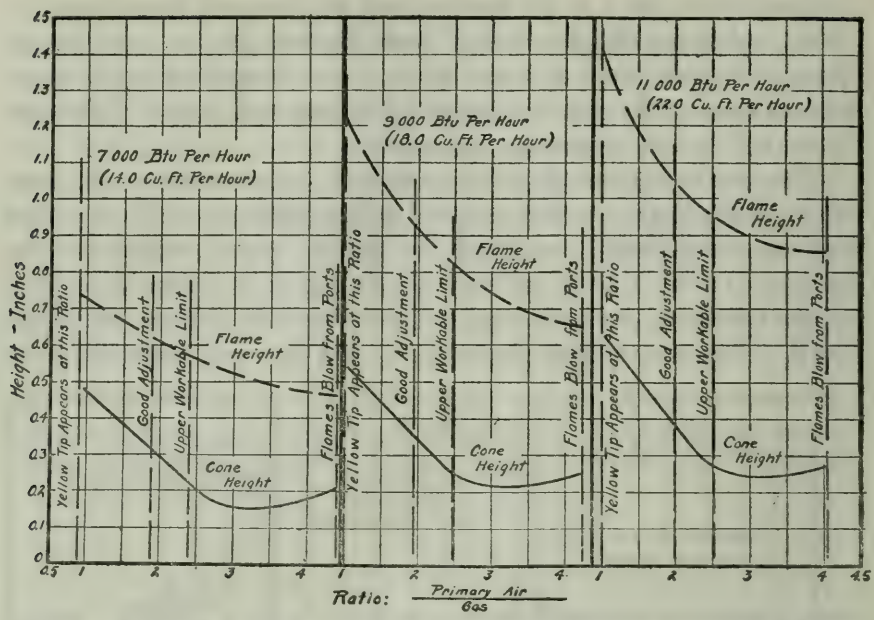

FIG. 59.—*Cone and flame heights with varying air-gas ratios when burner No. 1 is operated with 500 B. t. u. water gas at rates of 7,000, 9,000, and 11,000 B. t. u. per hour.*

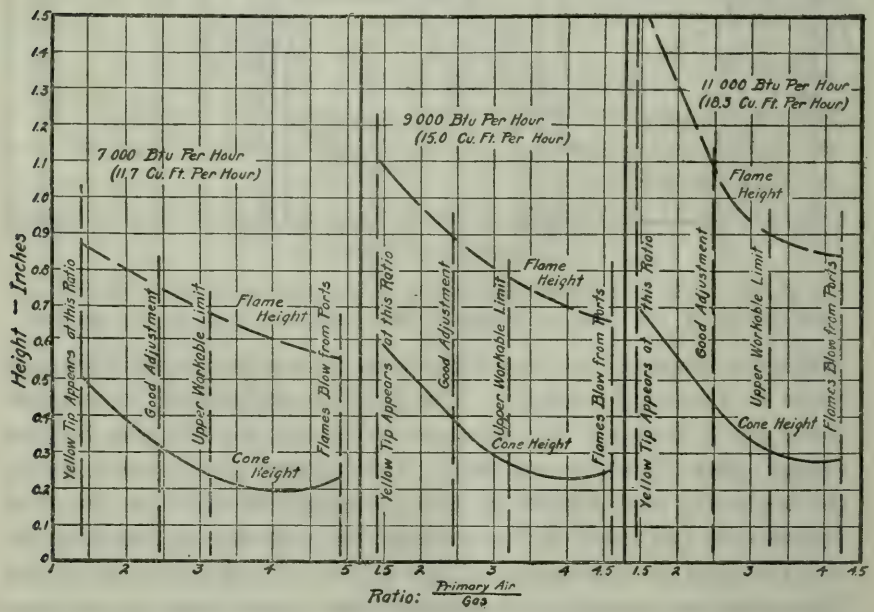

FIG. 60.—*Cone and flame heights with varying air-gas ratios when burner No. 1 is operated with 600 B. t. u. water gas at rates of 7,000, 9,000, and 11,000 B. t. u. per hour.*

burn, is decreased. But as the primary air approaches the amount required to completely burn the gas the velocity of combustion increases less rapidly, while the increase of the velocity of the mixture through the ports increases with the same rapidity. When this increase exceeds the increase of rate of combustion the cone will lengthen, as is shown by the cone-height curves in the various figures. It will be noted from Figures 58, 59, and 60 that when the cone height increases with an increase of air-gas ratio this

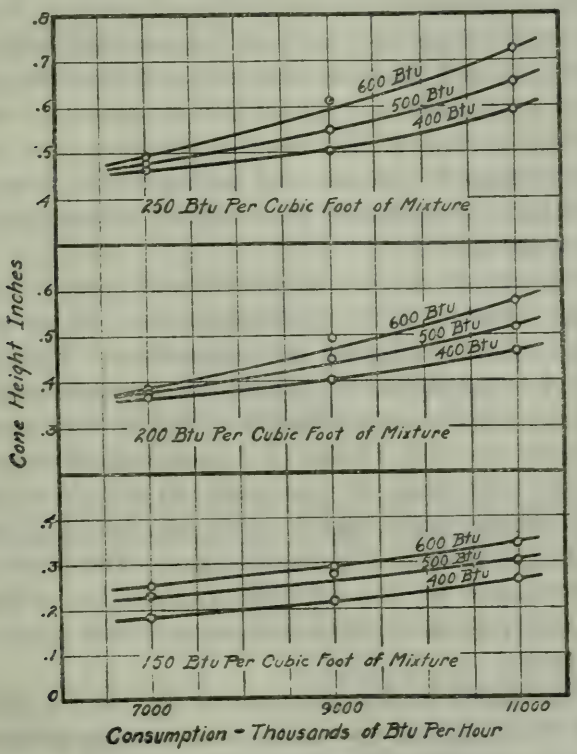

FIG. 61.—*Comparison of cone heights with 400, 500, and 600 B. t. u. water gas at 250 B. t. u. per cubic foot of mixture within the burner (soft flame, yellow tip), 200 B. t. u. per cubic foot of mixture (medium flame), and 150 B. t. u. per cubic foot of mixture (hard flame).*

Values taken from Figs. 58, 59, and 60.

ratio is beyond the limit of upper workable adjustment where burners will give satisfactory service.

Cone heights taken from Figures 58, 59, and 60 have been plotted in Figure 61 for rates of consumption of 7,000, 9,000, and 11,000 B. t. u./hr. and for three types of flames. Figure 61 summarizes the data given in the other figures and shows clearly the effect of heating value, gas rate, and air-gas ratio on the cone height.

VII. EFFECT OF CHANGE OF SPECIFIC GRAVITY OF GAS ON THE OPERATION OF A BURNER WHEN THE ADJUSTMENT REMAINS UNCHANGED.

The practice of mixing different kinds of gases has become quite common as a result of the increase in the development of the coke-oven processes with the production of by-product gas, the building of combination coal and water gas plants, and the necessity of supplementing the supply of natural gas with different kinds of manufactured gases.

The quantity of gas sent out from the gas works will vary greatly with the daily and seasonal demand, and since no combination method of manufacture is so flexible in operation as to supply the mixture always in the same proportion, the mixture will inevitably change in gravity and perhaps, to a lesser extent, in heating value. It is usually less difficult to control the heating value than the gravity.

One objection to the use of mixtures of gases is the difficulty of making adjustments in the appliances to secure good service when the mixtures change in composition. This question of variation of composition and gravity on the operation of burners has been discussed in considerable detail in this bureau's Technologic Paper No. 193, Design of Atmospheric Gas Burners. An attempt has been made in that paper to explain why it is more difficult to change from coal or coke-oven gas to water gas than from water gas to coal or coke-oven gas. The reader is referred to that discussion for the scientific explanation of the variation in the quantity of air injected into burners with gases of different specific gravity.

It will be shown in the calculations that follow just what the effect will be on burner operation when the gas pressure, heating value, and the burner adjustment are kept constant and the specific gravity only is changed. From data taken in these tests and reported elsewhere it has been shown that for a burner operated at the "good adjustment," the heating value per cubic foot of mixture within the burner is about 175 B. t. u. Taking this condition as the initial adjustment, the data given in Tables 40 and 41 have been calculated and are explained in more or less detail in the text that follows:

1. EFFECT OF CHANGE FROM 0.40 SPECIFIC GRAVITY COKE-OVEN GAS TO 0.65 SPECIFIC GRAVITY WATER GAS.

If a top burner is adjusted for a gas rate of 18 ft.³/hr. of *500 B. t. u. coke-oven gas of 0.40 specific gravity*, the consumption will be 9,000 B. t. u./hr. (See curve *C*, Fig. 62.) With this gas the air-gas ratio for the good adjustment is 1.85 when the mixture within the burner has a heating value of 175 B. t. u./ft.³ If the burner is now supplied with *500 B. t. u. water gas* (specific gravity 0.65) without changing the pressure or adjustment of the appliance, the gas rate will be decreased to 14.14 ft.³/hr., and the air-gas ratio will be increased to 2.41. The rate at which heat is now supplied is 7,070 B. t. u./hr. and the B. t. u. per cubic foot of mixture within the burner has been changed to 146.5. Referring to Figure 62, curve *C*, it will be seen that the new operating condition falls directly upon the line determining the upper workable limit of operation. With an initial adjustment for a lower rate per hour, the new condition would fall slightly above the upper workable limit and some difficulty from flash back might be experienced with the appliance. Also, if the initial adjustment had been made for a harder flame than that represented by 175 B. t. u./ft.³ (normal flame) there would be a much greater tendency for trouble at the new condition.

TABLE 40.—Effect of Increase in Specific Gravity of Gas (from 0.40 to 0.65) on the Operation of a Burner when Adjustment Remains Unchanged—Burner No. 1, 48 Ports, No. 40 Drill—Heating Value of Gas "500" B. t. u./ft.³—Gas Pressure 3.0 Inches of Water.

[See Fig. 62.]

Change of specific gravity of gas.		Quantity of heat supplied.	Gas rate.	Primary air-gas ratio.	B. t. u. per cubic foot of mixture.
		B. t. u./hr.	Ft.³/hr.		
A	from 0.40	7,000	14.0	1.85	175
	to .65	5,500	11.0	2.41	146.5
B	from .40	8,000	16.0	1.85	175
	to .65	6,280	12.56	2.41	146.5
C	from .40	9,000	18.0	1.85	175
	to .65	7,070	14.14	2.41	146.5
D	from .40	10,000	20.0	1.85	175
	to .65	7,850	15.70	2.41	146.5
E	from .40	11,000	22.0	1.85	175
	to .65	8,630	17.27	2.41	146.5

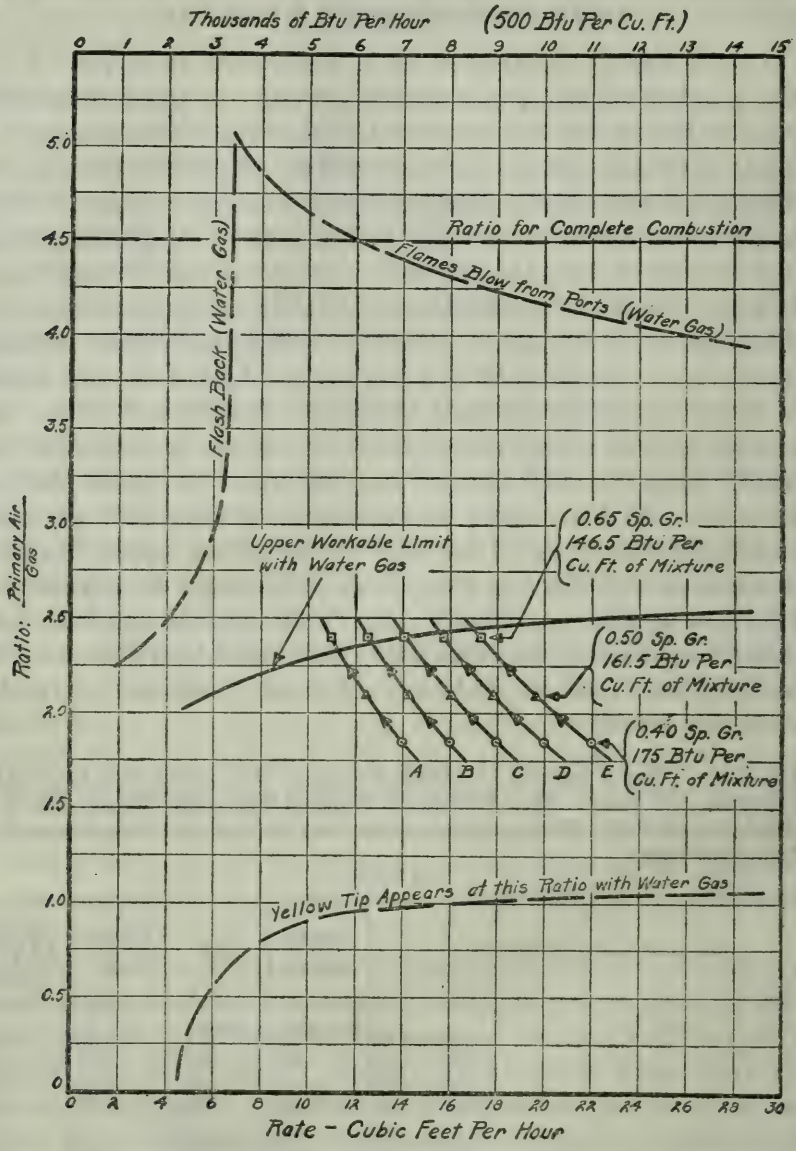

FIG. 62.—*Curves showing how the air-gas ratio increases and gas rate decreases with an increase of specific gravity.*

This figure applies to the case where an initial adjustment of the burner is made for 0.4 specific gravity (coal or coke-oven gas) and a normal flame (175 B. t. u. per cubic foot of mixture within the burner), and the specific gravity is then increased by mixing the coal or coke-oven gas with water gas or straight water gas of 0.65 specific gravity. It is assumed that no readjustment of the burner is made for the change in specific gravity. Curves (A, B, C, D, E) show the variation in air-gas ratio from five different initial adjustments.

The reduction from a rate of 9,000 to 7,070 B. t. u./hr. will increase the time required to do the first stages of cooking; but as this is still far above the rate required for keeping the contents of a vessel at boiling temperature, the reduction in rate should not materially interfere with the service. It has been found from experience that when changing from a coal or coke-oven gas to water gas, or from any light gas to a heavier gas, less difficulty is experienced if the heavier gas is of higher heating value than the light gas. This experience is in harmony with the physical principles explained in this paper. Briefly stated, the reason that an increase in the heating value of the heavier gas improves service is that a condition of good adjustment seems to represent a fairly definite B. t. u. mixture for all kinds of gas, and if the heavier gas is of higher B. t. u., the total rate in B. t. u. per hour supplied to the appliance and the mixture in B. t. u. per cubic foot of mixture will remain more constant.

2. EFFECT OF CHANGE FROM 0.65 SPECIFIC GRAVITY WATER GAS TO 0.40 SPECIFIC GRAVITY COKE-OVEN GAS.

If the initial adjustment in this case is made for 9,000 B. t. u./hr. with 500 B. t. u. water gas of 0.65 specific gravity, the gas rate will be 18 ft.^{3}/hr.; and if the air shutter is adjusted for an air-gas ratio of 1.65, the mixture will contain 175 B. t. u./ft.^{3}, which we have stated represents the condition of an average good adjustment. A change of gas to 500 B. t. u. coke-oven gas of 0.40 specific gravity, without any change in the burner adjustment, will increase the gas rate to 22.96 ft.^{3}/hr. (equivalent to 11,480 B. t. u./hr.), while the air-gas ratio will be decreased to 1.42 and the heating value per cubic foot of mixture is increased to 207 B. t. u. Although the air-gas ratio has been reduced and the heating value of the mixture increased we have a fairly good, although a soft, flame. The gas rate with the burner cock wide open is, of course, too large for good over-all efficiency, though the consumers will not ordinarily make a complaint about too much gas. However, unless they turn the gas partly off at the cock there will be a tendency toward waste.

The discussion in this and the preceding section shows that where the heating value of the gas or the specific gravity varies, it is necessary to consider the effect of the change on the composition of the mixture and the total B. t. u. consumption and adjust the burners accordingly.

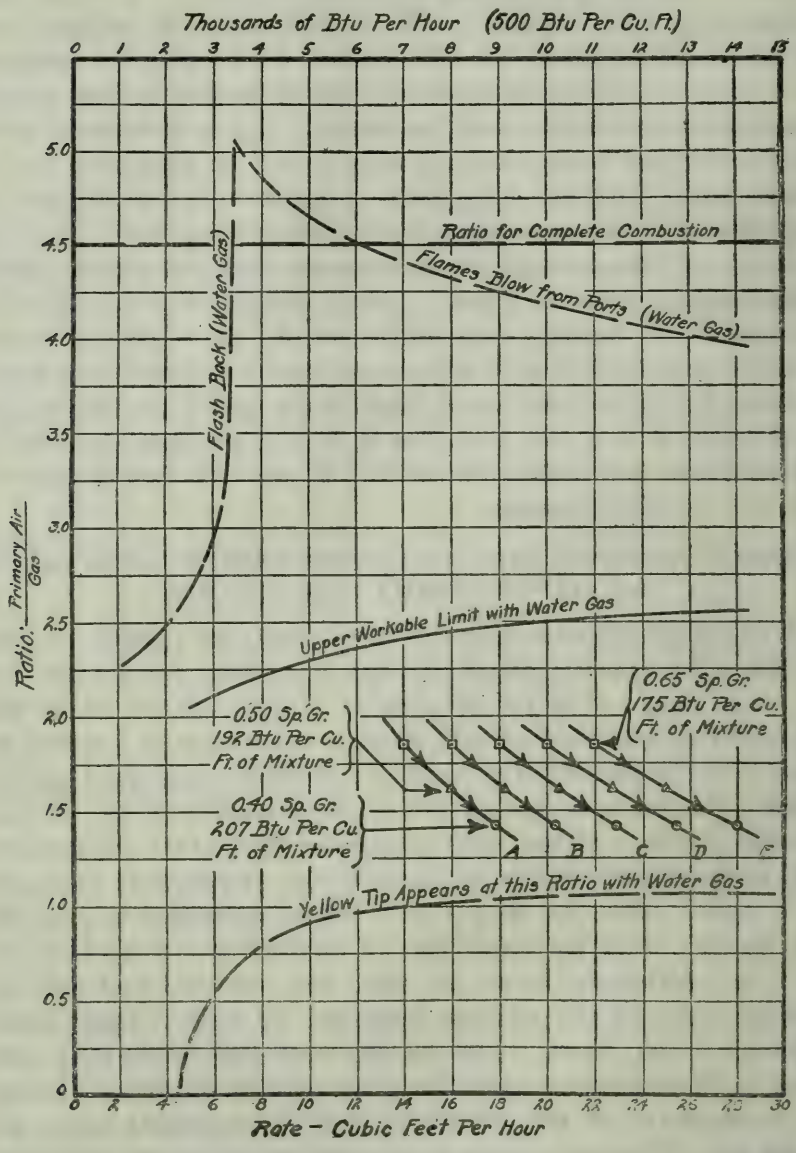

FIG. 63.—*Curves showing how the air-gas ratio decreases and gas rate increases with a decrease of specific gravity.*

This figure applies to the case where an initial adjustment of the burner is made for 0.65 specific gravity (water gas) and a normal flame (175 B. t. u. per cubic foot of mixture within the burner), and the specific gravity is then decreased by mixing the water gas with coal or coke-oven gas, or straight coal or coke-oven gas, of 0.40 specific gravity. It is assumed that no readjustment of the burner is made for the change in specific gravity. Curves (A, B, C, D, E) show the variation in air-gas ratio from five different initial adjustments.

TABLE 41.—Effect of Decrease of Specific Gravity of Gas (from 0.65 to 0.40) on the Operation of a Burner when Adjustment Remains Unchanged—Burner No. 1, 48 Ports, No. 40 Drill—Heating Value of Gas "500" B. t. u./ft.^{3}—Gas Pressure 3.0 Inches of Water.

[See Fig. 63.]

Change of specific gravity of gas.		Quantity of heat supplied.	Gas rate.	Primary air-gas ratio.	B. t. u. per cubic foot of mixture.
		B. t. u./hr.	Ft.^{3}/hr.		
A	from 0.65	7,000	14.0	1.85	175
	to .40	8,930	17.85	1.42	207
B	from .65	8,000	16.0	1.85	175
	to .40	10,200	20.4	1.42	207
C	from .65	9,000	18.0	1.85	175
	to .40	11,480	22.96	1.42	207
D	from .65	10,000	20.0	1.85	175
	to .40	12,750	25.5	1.42	207
E	from .65	11,000	22.0	1.85	175
	to .40	14,020	28.04	1.42	207

3. SUGGESTED ADJUSTMENT OF GAS RANGE BURNERS IN LOCALITIES WHERE THE SPECIFIC GRAVITY OF THE GAS VARIES.

Provided satisfactory and uniform pressure conditions can be maintained, it should be possible by a correct adjustment to maintain reasonably good service with most domestic appliances even with considerable variation in the gravity. The burners must be adjusted for an average condition which will make them operate under all conditions within the three limitations prescribed for good service. These limitations are:

(1) The adjustment must be such that in changing to the heavier gas the rate in B. t. u. per hour will not be less than a certain minimum which experience has shown is necessary for good service.

(2) The adjustment must be such that when the burners are operated with the heavier gas the air injection is not too great to cause the burners to flash back when operated at low rates of consumption.

(3) The adjustment must be such that when the burners are operated with the light gas, which results in increased gas rate and reduced air injection, the flames will not be yellow, odors will not be produced, nor the utensils or mantles blackened.

If the burners are adjusted when the composition of the gas represents equal proportions of the two gases of widely different specific gravity, within the limits found in ordinary practice, no serious difficulty should be experienced in operating the appliances with either the high or low specific gravity gas, since the effect of

changing to one or the other will not change the rate in B. t. u. per hour or the flame characteristics sufficiently to cause poor service or considerable loss in efficiency.

If the gas supply is composed mostly of the heavier gas at the time the burner adjustments are made, the best average adjustment is secured if the burners are adjusted for a gas rate slightly below the normal rate and the air shutters are set so that the flame is a little harder than a normal flame. If, on the other hand, the gas supply is composed mostly of the lighter gas at the time the burner adjustments are made, the best average adjustment is obtained by regulating the gas rate to slightly above a normal rate and by setting the air-shutter position to produce flames a little softer than a normal flame.

In addition to the methods suggested by which to make a good average adjustment, other methods may be found practicable. Some change in gas pressure or heating value to compensate for changes in specific gravity might be feasible so as to maintain the required amount of heat at the appliance and yet secure a satisfactory flame.

VIII. EFFICIENCY OF GASES OF DIFFERENT HEATING VALUE WITH A CHANGE OF DISTANCE OF UTENSIL FROM BURNER AND CARBON MONOXIDE IN THE PRODUCTS OF COMBUSTION AT DIFFERENT POSITIONS.

The efficiency of a burner, as well as the amount of carbon monoxide produced, varies with the distance of the utensil from the burner, the rate of gas consumption, and the type of flame. As has been described in a previous section of this report, the size and appearance of the flame depends upon two things—the rate of gas consumption and the primary air-gas ratio. For a constant rate of consumption the appearance of the flame depends upon the amount of primary air injected into the burner which determines the heating value per cubic foot of mixture. When the heating value per cubic foot of mixture is 250 B. t. u. the flame is very soft, while for 150 B. t. u./ft.^{3} of mixture the flame is very hard.

If the B. t. u. per cubic foot of mixture is kept constant and the gas rate is varied over the ususal range of adjustment, the air-gas ratio will remain constant and the flame will possess the same degree of "hardness" or "softness," depending on the initial adjustment. The only difference caused by a change in the B. t. u. rate is in the flame volume.

This condition is analogous to turning the gas cock in actual use. If a burner is set for a medium flame (about 200 B. t. u./ft.^{3} of mixture) with the gas cock wide open and the cock is then partly turned off, the gas rate will be reduced, but the air-gas ratio will remain practically the same, the B. t. u. per cubic foot of mixture will remain practically unchanged, and, therefore, the type of flame will be about the same, while the flame volume will be less. The efficiency will not be the same in both cases, as the degree of flame contact will differ.

What has been said previously is illustrated in the following curves, Figures 64 to 67, inclusive, which were obtained by operating tests of two burners, burner No. 1 and burner No. 3: Each burner was tested with water gas of both 500 and 600 B. t. u./ft.^{3} The curves were obtained by varying the gas rate and the distance of the utensil from the burner when the B. t. u. per cubic foot of mixture was a constant. Three different adjustments were made for each heating value of gas, namely, 150, 200, and 250 B. t. u./ft.^{3} of mixture. The efficiency tests reported in this section were made when the utensil was suspended from an adjustable support. All the previous efficiency tests were made on stoves with grid tops, and it will be observed that slightly higher values were secured on the stoves. The explanation for this difference in the results may be that with the use of the grid there was a greater restriction to the escape of the products of combustion, which in turn reduced the supply of secondary air, lengthened the flame, and resulted in better flame contact.

1. TESTS OF BURNER NO. 1 WITH 500 AND 600 B. T. U. WATER GAS.

The curves, Figures 64 and 65, were obtained by operating the burner with 500 and 600 B. t. u. water gas. The time and efficiency curves, Figure 64A, with 500 B. t. u. gas, were made at rates of 7,000, 9,000, and 11,000 B. t. u./hr. at four different positions, while the adjustment of the burner was kept constant at 150 B. t. u./ft.^{3} of mixture. In a similar manner the curves in Figure 64, *B* and *C*, were made by changing the B. t. u. per cubic foot of mixture. Tests were made with 600 B. t. u. gas in similar manner and the results are shown in Figure 65.

The position of the burner relative to the utensil has a marked effect on the efficiency. It will be noted in referring to the accompanying figures that as the distance between utensil and burner is increased there is a decrease in efficiency. This is due to a decrease

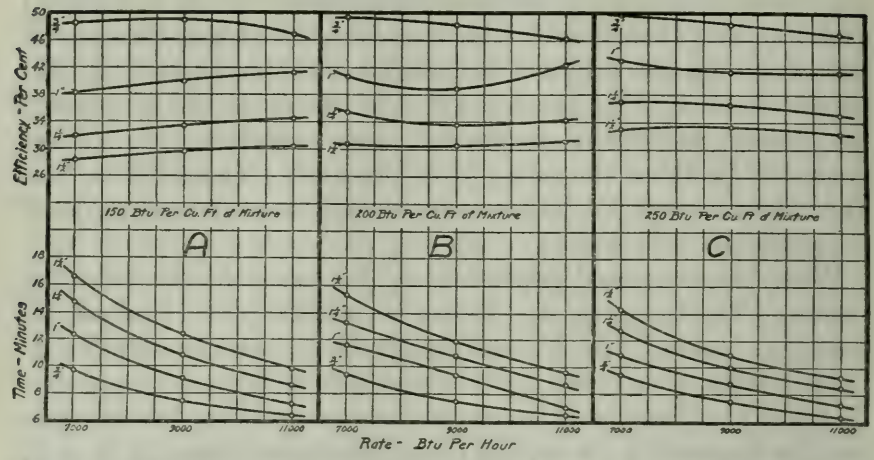

FIG. 64.—*Curves showing efficiency obtained with change of distance of utensil from burner.*

Tests made with burner No. 1, 500 B. t. u. water gas and three types of flame. Chart A obtained with 150 B. t. u. per cubic foot of mixture within the burner (hard flame); Chart B, 200 B. t. u. per cubic foot of mixture (medium flame); Chart C, 250 B. t. u. per cubic foot of mixture (soft flame—yellow tip).

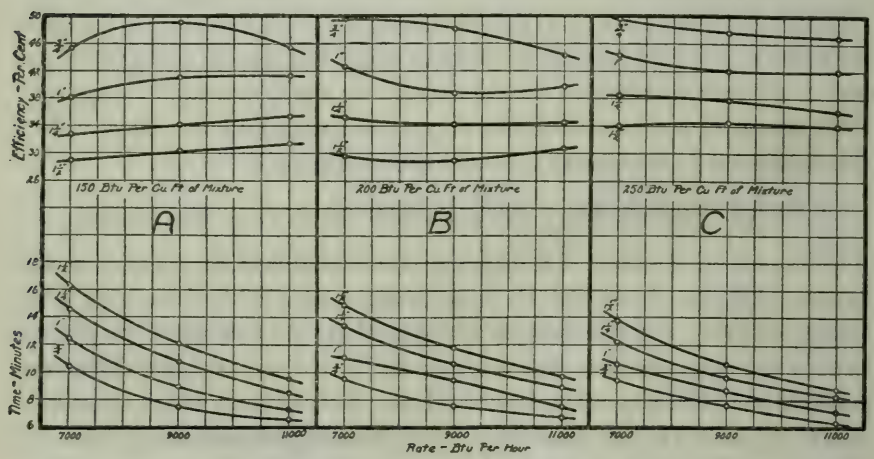

FIG. 65.—*Curves showing efficiency obtained with change of distance of utensil from burner.*

Tests made with burner No. 1, 600 B. t. u. water gas and three types of flame. Chart A obtained with 150 B. t. u. per cubic foot of mixture within the burner (hard flame); Chart B, 200 B. t. u. per cubic foot of mixture (medium flame); Chart C, 250 B. t. u. per cubic foot of mixture (soft flame—yellow tip).

in the amount of flame contact. The decrease in efficiency caused by moving the utensil from the ¾-inch to the 1½-inch position amounts to about 15 per cent irrespective of the gas rate.

At the ¾-inch position the higher gas rate gives a lower efficiency. The efficiency tends to increase with the amount of flame contact until the flame begins to extend up the side of the utensil. When this occurs a large part of the available heat in the flame is lost by radiation and convection and the efficiency decreases. This is what happens when the rate is 11,000 B. t. u./hr. for the ¾-inch position.

The efficiency varies only slightly with a change of gas rate for the usual distance of utensil from burner. When the gas rate is increased there is an accompanying increase in the flame volume and, as shown by the curves, the efficiency is slightly greater for 11,000 B. t. u./hr. than for the 7,000 B. t. u./hr. rate only with the hard flame.

The efficiency will vary with the type of flame. There is a difference in the flame volume for the adjustments of 150, 200, and 250 B. t. u./ft.^{3} of mixture. It is, therefore, evident that when the utensil is in any one position the flame contact for these three adjustments will not be the same and, therefore, the efficiency will differ. Since the efficiency depends almost entirely on good flame contact there is some one position for each type of flame that will give a maximum heat absorption. Whether the type of flame corresponding to 150, 200, or 250 B. t. u./ft.^{3} of mixture for any particular gas rate gives the best efficiency depends on the distance between the burner and the utensil.

All the curves are similar for the 500 and 600 B. t. u. water gas for the same burner. It will be noted that the curves for 600 B. t. u. water gas are almost identical with those obtained when using 500 B. t. u. water gas, which shows that the heating value of the gas makes no difference in the efficiency of a burner, provided that the comparison is made when the B. t. u. per cubic foot of mixture is constant.

2. TESTS OF THE BURNER NO. 3 WITH 500 AND 600 B. T. U. WATER GAS.

The curves shown in Figures 66 and 67 for this burner were determined in the same way as was done in the case of Burner No. 1. The same conclusions can be drawn in connection with this burner as were pointed out with reference to the other. It will be noted that the efficiencies obtained with this burner are consistently higher

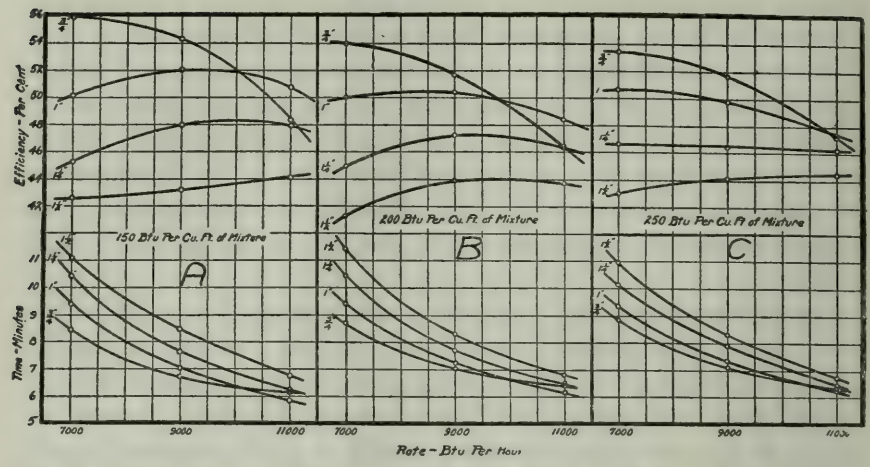

FIG. 66.—*Curves showing efficiency obtained with change of distance of utensil from burner.*

Tests made with burner No. 3, 500 B. t. u. water gas and three types of flame. Chart A obtained with 150 B. t. u. per cubic foot of mixture within the burner (hard flame); Chart B, 200 B. t. u. per cubic foot of mixture (medium flame); Chart C, 250 B. t. u. per cubic foot of mixture (soft flame—yellow tip).

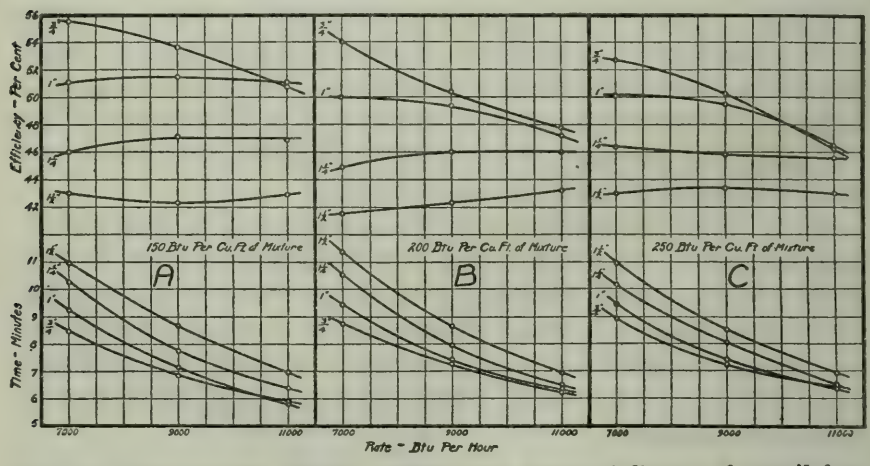

FIG. 67.—*Curves showing efficiency obtained with change of distance of utensil from burner.*

Tests made with burner No. 3, 600 B. t. u. water gas and three types of flame. Chart A obtained with 150 B. t. u. per cubic foot of mixture within the burner (hard flame); Chart B, 200 B. t. u. per cubic foot of mixture (medium flame); Chart C, 250 B. t. u. per cubic foot of mixture (soft flame—yellow tip).

than those obtained for similar adjustments with Burner No. 1. This is due in a large measure to the tendency of the flame to incline toward the center and thus give a concentration of heat at this point. This type of burner is such that there is insufficient aeration of the flame, which results in an increase in the flame volume, and therefore better flame contact. The effect of flame volume is markedly shown by referring to Figure 67C, which gives results on a burner adjusted to a soft flame (250 B.t.u./ft.^{3} of mixture). When the utensil is placed three-fourths inch from the burner with a gas rate of 11,000 B.t.u./hr. the flame volume is so great that the corresponding heat lost by radiation and convection lowers the efficiency to that obtained at the 1-inch position.

The minimum distance between utensil and burner is determined by the production of carbon monoxide. It has been pointed out in the foregoing that for all adjustments the closer the utensil is placed to the burner the higher the efficiency obtained. However, when a utensil is placed so close to a burner that there is cone contact, carbon monoxide is produced. As this gas, even when present in the room atmosphere in small quantities, is detrimental to health, it is advisable to place the utensil at a distance from the burner that will give the highest obtainable efficiency without the formation of carbon monoxide.

Tables 42, 43, 44, and 45 were prepared from analyses of the products of combustion from Burner No. 1 and Burner No. 3 and also from careful observations of the appearance of the flame for the different conditions of test. Tables 42 and 43 for Burner No. 1 show that the position chosen should be about 1 inch, while Tables 44 and 45 for Burner No. 3 show that the utensil should not be placed closer than about 1½ inches.

TABLE 42.—Carbon Monoxide in Products of Combustion from "500" B. t. u. Water Gas When Burner is at Different Distances from Utensil—Burner No. 1, 48 Ports, No. 40 Drill.

Quantity of heat supplied (B.t.u./hr).	Distance of utensil from burner.	150 B.t.u./ft.³ of mixture (hard flame).		200 B.t.u./ft.³ of mixture (medium flame).		250 B.t.u./ft.³ of mixture (soft flame, yellow tip).	
		CO produced.	Remarks.	CO produced.	Remarks.	CO produced.	Remarks.
	Inches.	Ft.³/hr.		Ft.³/hr.		Ft.³/hr.	
7,000 (14 ft.³).	¾	0	General flame contact.	0.05	Slight cone contact. General flame contact.	0.17	General cone contact.
	1	0	Slight flame contact.	0	General flame contact.	Trace.	Some cones extend to utensil.
	1¼	0	No flame contact..	0	Slight flame contact.	0	General flame contact.
	1½	0	.....do.....	0	No flame contact..	0	Slight flame contact in center.
9,000 (18 ft.³).	¾	0.07	Some cones extend to utensil. Flame extends up side of utensil.	.11	Cones extend to utensil. Flame extends up side of utensil.	.17	All cones extend to utensil. Flame extends up side of utensil.
	1	0	General flame contact.	0	General flame contact.	Trace.	Slight cone contact.
	1¼	0	Slight flame contact.	0	Flame contact.....	0	Flame contact.
	1½	0	A little flame contact at center.	0	Slight flame contact.	0	Slight flame contact.
11,000 (22 ft.³).	¾	.29	About one-half cones extend to utensil.	.25	Most of cones extend to utensil. Flame extends up side of utensil.	.27	All cones extend to utensil. Flame extends up side of utensil.
	1	0	General flame contact.	Trace.	Slight cone contact. General flame contact.	Trace.	Slight cone contact. Flame extends up side of utensil.
	1¼	0	Flame contact.....	0	General flame contact.	0	General flame contact.
	1½	0	A little flame contact.	0	Flame contact.....	0	Flame contact.

TABLE 43.—Carbon Monoxide in Products of Combustion from "600" B. t. u. Water Gas When Burner is at Different Distances from Utensil—Burner No. 1, 48 Ports, No. 40 Drill.

Quantity of heat supplied (B.t.u./hr).	Distance of utensil from burner.	150 B.t.u./ft.³ of mixture (hard flame).		200 B.t.u./ft.³ of mixture (medium flame).		250 B.t.u./ft.³ of mixture (soft flame, yellow tip).	
		CO produced.	Remarks.	CO produced.	Remarks.	CO produced.	Remarks.
	Inches.	Ft.³/hr.		Ft.³/hr.		Ft.³/hr.	
7,000 (11.7 ft.³).	¾	0	Flame contact.....	0.05	A few cones extend to utensil. Flame contact.	0.20	Cones extend to utensil. General flame contact.
	1	0	Slight flame contact.	Trace.	Slight cone contact. Flame contact.	Trace.	Slight cone contact. Flame contact.
	1¼	0	No flame contact..	0	Slight flame contact.	0	General flame contact.
	1½	0	.....do.....	0	No flame contact..	0	Flame contact at center.
9,000 (15 ft.³).	¾	0.15	Few cones extend to utensil.	.08	Some cones extend to utensil.	.20	Cones extend to utensil. Flame extends up side of utensil.
	1	0	Flame contact.....	0	General flame contact.	Trace.	Slight cone contact. Flame extends up side of utensil.
	1¼	0	Slight flame contact.	0	Slight flame contact.	0	General flame contact.
	1½	0	No flame contact..	0	No flame contact..	0	Slight flame contact.
11,000 (18.3 ft.³).	¾	.22	Most of cones extend to utensil.	.24	General cone contact.	.18	General cone contact. Flame extends up side of utensil.
	1	Trace.	General flame contact. Slight cone contact.	Trace.	Slight cone contact.	Trace.	Slight cone contact. Flame extends up side of utensil.
	1¼	0	Slight flame contact.	0	General flame contact.	0	Flame extends up side of utensil.
	1½	0	Flame contact at center.	0	Flame contact.....	0	General flame contact.

TABLE 44.—Carbon Monoxide in Products of Combustion from "500" B. t. u. Water Gas When Burner is at Different Distances from Utensil—Burner No. 3, 45 Ports, No. 38 Drill.

Quantity of heat supplied. (B.t.u./hr.).	Distance of utensil from burner.	150 B.t.u./ft.³ of mixture (hard flame).		200 B.t.u./ft.³ of mixture (medium flame).		250 B.t.u./ft.³ of mixture (soft flame, yellow tip).	
		CO produced.	Remarks.	CO produced.	Remarks.	CO produced.	Remarks.
	Inches.	Ft.³/hr.		Ft.³/hr.		Ft.³/hr.	
7,000 (14 ft.³).	¾	0.18	Cone contact at outer ports.	0.20	Cone contact at outer ports.	0.19	General cone contact.
	1	Trace.	Slight cone contact.	Trace.	Slight cone contact. Flame contact.	.05	A few cones extend to utensil.
	1¼	0	No flame contact...	0	Slight flame contact.	0	Slight flame contact.
	1½	0	.....do.....	0	No flame contact...	0	No flame contact.
9,000 (18 ft.³).	¾	.20	Cone contact except at the central ports.	.23	Cone contact except at central ports. Flame extends up side of utensil.	.28	General cone contact. Flame extends up side of utensil.
	1	.12	Cone contact at outer ports.	.11	Cone contact at outer ports.	.12	Cone contact at outer ports.
	1¼	Trace.	A few cones extend to utensil.	Trace.	A few cones extend to utensil.	Trace.	A few cones extend to utensil.
	1½	0	Slight flame contact.	0	Flame contact.....	0	Flame contact.
11,000 (22 ft.³).	¾	.22	General cone contact. Flame extends up side of utensil.	.20	General cone contact. Flame extends up side of utensil.	.23	General cone contact. Flame extends up side of utensil.
	1	.19	Outer cones extend to utensil. Flame extends up side of utensil.	.17	Outer cones touch utensil. Flame extends up side of utensil.	.15	Outer cones touch utensil. Flame extends up side of utensil.
	1¼	.09	A few cones extend to utensil. Flame extends up side of utensil.	.10	A few cones extend to utensil. Flame extends up side of utensil.	.08	A few cones extend to utensil. Flame extends up side of utensil.
	1½	0	General flame contact.	Trace.	Slight cone contact. General flame contact.	Trace.	Slight cone contact. General flame contact.

TABLE 45.—Carbon Monoxide in Products of Combustion from "600" B. t. u. Water Gas When Burner is at Different Distances from Utensil—Burner No. 3, 45 Ports, No. 38 Drill.

Quantity of heat supplied (B.t.u./hr.).	Distance of utensil from burner.	150 B.t.u./ft.³ of mixture (hard flame).		200 B.t.u./ft.³ of mixture (medium flame).		250 B.t.u./ft.³ of mixture (soft flame, yellow tip).	
		CO produced.	Remarks.	CO produced.	Remarks.	CO produced.	Remarks.
	Inches.	Ft.³/hr.		Ft.³/hr.		Ft.³/hr.	
	¾	0.15	Cone contact at outer ports.	0.16	Cone contact at outer ports. Flame extends up side of utensil.	0.19	General cone contact. Flame extends up side of utensil.
7,000 (11.7 ft.³).	1	Trace.	A few outer cones extend to utensil.	Trace.	A few cones extend to utensil.	Trace.	Slight cone contact.
	1¼	0	No flame contact...	0	Slight flame contact.	0	Slight flame contact.
	1½	0	.....do.....	0	No flame contact...	0	No flame contact.
	¾	.19	Cone contact. Flame contact.	.21	Cone contact. Flame extends up side of utensil.	.24	General cone contact. Flame extends up side of utensil.
9,000 (15 ft.³).	1	.10	Slight cone contact.	.12	Cone contact at outer ports. Flame extends up side of utensil.	.13	Cone contact. Flame extends up side of utensil.
	1¼	Trace.	.....do.....	Trace.	Slight cone contact.	Trace.	Slight cone contact.
	1½	0	No flame contact...	0	Slight flame contact.	0	Slight flame contact.
	¾	.25	Cones extend to utensil. Flame extends up side of utensil.	.24	Cones extend to utensil. Flame extends up side of utensil.	.19	General cone contact. Flame extends up side of utensil.
11,000 (18.3 ft.³).	1	.19	Cones extend to utensil.	.15	Cone contact.....	.14	Cone contact. Flame extends up side of utensil.
	1¼	.07	A few cones extend to utensil.	.05	Slight cone contact.	.06	Slight cone contact. Flame extends up side of utensil.
	1½	0	Flame contact.....	0	General flame contact.	0	General flame contact.

IX. EFFECT OF CAREFUL OPERATION OF GAS BURNERS ON GAS CONSUMPTION.

Many cooking processes require the heating of the water in the utensil up to boiling and the maintenance of the boiling temperature (212° F.) thereafter until the food is completely cooked. Some people forget or do not know that water can not be heated to a temperature higher than 212° F. at atmospheric pressure and that violent boiling does not accelerate the speed of cooking. It only evaporates water needlessly, wastes gas, and causes the consumer to complain of high gas bills.

Some idea of the difference between careless operation and careful operation of an appliance can be gained from the tests reported in Table 46.

TABLE 46.—Tests of Evaporation of Water with "City Gas" of 502 B. t. u.

Test No.	Gas rate.	Quantity of heat supplied.	Quantity of water used.	Time required for complete evaporation.	Remarks.
	Ft.³/hr.	B. t. u./hr.	Quarts.	Hours.	
1	2.05	1,030	2	9.15	Lid on, gentle boiling.
2	10.62	5,330	2	1.49	Lid off, gentle boiling.
3	18.42	9,250	2	1.13	Lid on, violent boiling.
4	18.50	9,290	2	1.10	Lid off, violent boiling.

NOTE.—To make the lid-on tests a piece of plate glass was placed over the utensil in order to observe the degree of boiling. A small opening corresponding to a loose-fitting lid allowed the steam to escape. In tests Nos. 1 and 2 the water was in a state of gentle boiling, whereas in Nos. 3 and 4 the water was violently agitated by the boiling.

The following important conclusions may be drawn from these evaporation tests:

1. With a lid on the utensil, violent boiling (gas on full) consumes about nine times more gas than is necessary to maintain gentle boiling.

2. For gentle boiling about five times as much gas is used with the lid off as would be required if a lid were on the utensil.

3. When violently boiled the water evaporates at about the same rate with the lid on as with the lid off.

4. Gentle boiling evaporates water about six times as fast with the lid off as compared with the lid on.

X. SUMMARY.

In connection with an investigation conducted by the Public Service Commission of Maryland to determine the most economic heating-value standard for manufactured gas in the city of Baltimore, the Bureau of Standards carried on an extensive series of laboratory tests of gases of different heating value and composition.

In this report of the laboratory tests are discussed three of the many important factors that must be considered in determining the relative service value of different gases. They are (1) what is the relative utilization efficiency of gases of different heating value when each gas is tested under the most practical conditions? (2) to what extent can the present appliances be adapted to give good and efficient service with gases of different heating value and composition? (3) what adjustment in appliances is necessary to give the consumers good and efficient service when different kinds of gases are mixed and the composition, heating value, and the specific gravity change as a result of daily and seasonal variations in the send out?

1. RELATIVE UTILIZATION EFFICIENCY OF GASES OF DIFFERENT HEATING VALUE.

Since it is desirable to compare the relative efficiency of gases of different heating value under conditions most favorable to each gas, it is necessary to consider the effect of air-shutter adjustment, distance of utensil from the burner, and the gas rate.

The efficiency of a burner varies with the type of flame. The size and appearance of a flame depend upon the composition of the gas, the gas rate, the heating value, and the primary air-gas ratio. The heating value and ratio of primary air to gas determine the B. t. u. per cubic foot of the mixture within the burner. An adjustment that gives a mixture of gas and air within the burner with a heating value of 250 B. t. u./ft.^{3} gives a very soft flame, while a mixture of 150 B. t. u./ft.^{3} gives a very hard flame. The good adjustment for all the gases showed that the mixture had an average heating value of about 175 B. t. u./ft.^{3} If the gas rate is varied over the usual range of adjustment by a change in the pressure at the gas orifice, the flame volume will vary, but the B. t. u. per cubic foot of mixture remains practically constant and the flame will possess almost the same degree of "hardness" or "softness" (depending on the initial adjustment).

With a hard flame the efficiency tends to increase slightly with an increase in gas rate for any one distance of the utensil from burner. This is true, in general, except when the utensil is placed three-fourths inch or less from the burner. There is a difference in flame volume according to whether the adjustment is made for a soft, medium, or hard flame. It is evident, therefore, that when the utensil is in any one position the flame contact for these three adjustments will not be the same and, therefore, the efficiency will differ.

The distance between the burner and the utensil has a marked effect on the efficiency. The efficiency varies inversely as the distance between the utensil and burner and tends to increase with the amount of flame contact until the flame extends up the side of the utensil. When this occurs a large part of the available heat in the flame is lost by radiation and convection and the efficiency decreases.

Maximum efficiency can not be secured because of formation of carbon monoxide at close position of the utensil to burner. A distance of three-fourths inch, or less, would give the maximum efficiency; but when a utensil is placed so close to a burner that there is cone contact, carbon monoxide is produced. Since this

gas, even when present in the room atmosphere in small quantities, is detrimental to health, it is advisable to place the utensil at a distance from the burner that will give the highest efficiency without the formation of carbon monoxide. The results of these tests show that for the size of vessel used the minimum distance should be about 1 inch for Burner No. 1, while for Burner No. 3 the vessel should not be placed closer than about 1½ inches.

With burners properly located and adjusted the danger from carbon monoxide is remote with normal rates of gas consumption. The analyses show that with the ranges used, the burners of which were 1⅜ inches from the vessel, practically no carbon monoxide was produced with any of the gases tested, unless gas was burned at a rate greater than about 12,000 B. t. u./hr. Above this rate the amount of carbon monoxide produced was sufficient to cause headaches in a poorly ventilated room. The tests showed that the disk type of burner produced more carbon monoxide than the star type, when operated at the same distance (1⅜ inches) from utensil and at the same rate of consumption.

Although the production of carbon monoxide varied with the position and adjustment of burner and the rate of consumption, if the gases are compared under conditions that are considered proper for each gas, it can be said that the heating value or the kind of gas did not seem to be factors affecting the production of carbon monoxide.

After giving due consideration to the before-mentioned factors which have an influence on efficiency, we can draw the following conclusions from these laboratory tests:

(1) *Irrespective of the heating value of the gas, the efficiency (ratio of heat absorbed to heat contained in the gas burned) obtained with any one burner is very nearly constant, provided the burner is adjusted to consume the same number of B. t. u. per hour with each gas.* Thus, to heat a given quantity of water to the same temperature in the same time required 2 feet^3 of 300 B. t. u. gas to 1 foot^3 of 600 B. t. u. gas. In other words, the quantity of gas required varied inversely with the heating value of the gas.

(2) When the burners of standard size were adjusted for a gas rate of 9,000 B. t. u./hr., an efficiency of about 37 per cent was secured, and it required almost exactly 10 minutes to heat 2 quarts of water from 80° F. to boiling with each kind of gas. (See Table 33 and Fig. 50.) At a rate of 7,000 B. t. u./hr. an average efficiency of about 36 per cent was obtained with Burner No. 1 (see Table 32) and about 13 minutes were required. For a rate of 11,000

B. t. u./hr. the average efficiency was about 37.7 per cent (see Table 34) and the time required was about 8 minutes. *These results show that over the range of usual operating conditions the efficiency of heat absorption varies only slightly with a change in the rate of heat supply. It follows, therefore, that the rate of heating varies almost directly with the rate of supply of heat.*

2. EXTENT TO WHICH THE PRESENT APPLIANCES CAN BE ADAPTED TO GIVE GOOD AND EFFICIENT SERVICE WITH GASES OF DIFFERENT HEATING VALUE AND COMPOSITION.

(1) Appliances require less pressure to give good combustion with lower heating value gases. Tests of Burner No. 1 show that with 500 B. t. u. water gas a pressure of 1 inch is sufficient to give the required primary air for good adjustment, and with 600 B. t. u. water gas a pressure of about 1¼ inches is sufficient.

The best results are secured from appliances when the gas pressure is constant and the appliance is adjusted to give sufficient heat and good combustion at the average rate required for cooking. Since it is not economical to distribute gas at a very low pressure, the burners are usually adjusted for a pressure much higher than is actually required for a good operation of the appliance. In other words, the pressure that is carried in the gas mains is not determined entirely by the requirements of the appliances, but by distribution costs. Complaints of poor pressure are, therefore, often due not to insufficient pressure in the mains but to improper adjustment of the appliances.

(2) Burner No. 2 could be adjusted to 450 B. t. u. gas with a 3-inch pressure without any changes in the burner. With a gas of any lower heating value, a tighter-fitting air shutter would be required for a proper regulation of the primary air.

Burner No. 1 could be adjusted to 350 B. t. u. gas without any change in the appliance.

(3) The range of workable adjustments of a burner with coal gas is somewhat greater than with water gas. The tests show that the yellow flame occurs at a higher B. t. u. per cubic foot of mixture (lower air-gas ratio) and the upper limit of workable adjustment at a lower B. t. u. per cubic foot of mixture (higher air-gas ratio) with coal gas than with water gas.

The results on the whole show that present domestic range burners can be adjusted to give satisfactory service over a wide range in heating value, the slight differences in behavior of the different gases not being of sufficient importance to have much weight in any consideration of their relative merits for use in domestic appliances.

3. ADJUSTMENT IN APPLIANCES NECESSARY TO GIVE THE CONSUMERS GOOD AND EFFICIENT SERVICE, WHEN DIFFERENT KINDS OF GASES ARE MIXED AND THE COMPOSITION, HEATING VALUE, AND THE SPECIFIC GRAVITY CHANGE.

The development in the coke-oven processes with the production of by-product gas, the building of combination coal and water gas plants, and the necessity of supplementing natural gas with different kinds of manufactured gas has resulted in the delivery of mixed gases in many localities. The variation in heating value and specific gravity of the mixed gas may cause service troubles, unless the appliances are properly adjusted.

It is possible by a correct adjustment of appliances to maintain good service even with considerable variation in the gravity. The burners must be adjusted for an average condition which will permit them to be operated under all conditions within the three limitations prescribed for good service. These limitations are:

(1) The adjustment must be such that in changing to the heavier gas the rate in B. t. u. per hour will not be reduced below a certain minimum which experience has shown is necessary for good service.

(2) The adjustment must be such that when the burners are operated with the heavier gas, the air injection is not too great to cause the burners to flash back when operated at low rates of consumption.

(3) The adjustment must be such that when the burners are operated with the light gas, which results in increased gas rate and reduced air injection, the flames will not be yellow, odors will not be produced, nor the utensils or mantles blackened.

If a burner is adjusted when the composition of the gas represents equal proportions of two gases of widely different specific gravity, no difficulty should be experienced in operating the appliance with either the high or low specific gravity gas, since the effect of changing to one or the other will not change the rate in B. t. u. per hour nor the flame characteristics sufficiently to cause poor service or loss in efficiency.

If a burner is adjusted when the gas consists mostly of the heavier gas, the best average adjustment would be secured by regulating the gas rate slightly below the normal rate and by setting the air shutter to give a flame harder than a "normal" flame. If, on the other hand, the gas consists mostly of the lighter gas at the time the burner adjustment is made, the best

average adjustment would be obtained by regulating the gas rate to slightly above a normal rate and by setting the air shutter to produce a flame softer than a "normal" flame.

In addition to the methods suggested for making a good average adjustment, other methods may be found practicable. Some change in gas pressure or heating value to compensate for changes in specific gravity might be feasible so as to maintain the required amount of heat at the appliance and yet secure a satisfactory flame.

It is quite practicable, therefore, for appliance fitters to adjust domestic range burners so that the service will be satisfactory and there will be no appreciable loss in efficiency, even though the heating value, the specific gravity, and pressure vary over considerable limits. Certain types of gas lamps and industrial appliances which demand a rather constant B. t. u. rate per hour would not operate as satisfactorily under these conditions. In general, the less variation there is in heating value, composition, specific gravity, and gas pressure, the easier it is to adjust the appliances to the most ideal condition and the more satisfactory will be the service.

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RECLAMATION OF USED PETROLEUM LUBRICATING OILS

BY

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RECLAMATION OF USED PETROLEUM LUBRICATING OILS.

By Winslow H. Herschel and A. H. Anderson.

ABSTRACT.

Used lubricating oils may be reclaimed by apparatus already commercially available and thus saved for further use. Such reclaimed oils will pass all the commonly accepted tests for new oils, such as flash point, viscosity, and sediment. It is more doubtful whether the reclamation process sufficiently reduces the organic acidity and sulphur content, but there is some doubt whether this is necessary. There is little possibility that the organic acidity would ever be high enough in an uncompounded oil to cause corrosion. It is often the case that high acidity is accompanied by readiness of emulsification, but exceptions have been found, so that the value of the test for acidity must lie in the possibility that an oil of high acidity will not prove durable in use. When more is known concerning the best test for durability of an oil, it may be necessary to modify reclaiming methods, so that reclaimed oils may meet such test.

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I. INTRODUCTION.

There is an increasing demand for petroleum products for fuel and lubricants due to the increasing use of internal-combustion engines in the Navy, merchant marine, the omnipresent automobile, and elsewhere. The supply of crude oil from the petroleum fields of the United States can not be increased with the same rapidity, and it is already necessary to import crude oil from Mexico in large and increasing amounts. The petroleum reserves have been thoroughly investigated by the Geological Survey, and it is found that "a big fraction of the domestic petroleum is gone. Whether that fraction is one-third, as present

knowledge indicates, or is one-fourth or even one-fifth makes no difference in the consideration demanded by the situation."[1]

In the western part of the United States there is an abundance of oil shale, but the processes of extracting and refining the oil are still in the experimental state, and shale oil must be regarded as a product of the future rather than as a means already available for supplementing the petroleum from the wells.

Oil used as fuel is lost past recovery, but much of the lubricating oil which has been used and discarded as unfit for further service can be reclaimed. Automobile oils especially deteriorate rapidly in use, but the used oil may be restored to its original condition by processes already applied on a commercial scale in several cities. Thus, the reclamation of used oils furnishes a method, already available, of aiding in the conservation of an irreplaceable natural resource.

II. THE DETERIORATION OF LUBRICATING OILS IN USE.

It has become recognized as good practice, especially for high-speed machinery, to use a forced-feed lubricating system, the oil being pumped from a settling tank through the bearings and allowed to flow back to the tank. The oil is thus used over and over again, and under these conditions it gradually oxidizes and grows more viscous and may eventually form a deposit known as sludge.

There are additional causes of deterioration of oils which are used in internal-combustion engines, as in automobiles. The oil in the crank case is usally diluted by kerosene (the "heavy ends" or unvolatilized fraction of the gasoline) which tends to make the oil decrease in viscosity with use. On account of this crank-case dilution it is not always easy to distinguish between troubles due to the oil and those due to the fuel. When there is corrosion in the crank case, there is at least as much probability that it is due to sulphur in the fuel as to any property of the oil when new. There is also a possibility of dilution by a volatile product of "cracked" oil,[2] but the amount of this material may be assumed negligible in comparison with the heavy ends of the fuel. The conditions of use in an automobile cylinder are very severe, the oil film being exposed to great heat which burns away part of the oil, leaving so-called carbon deposits which

[1] C. G. Gilbert and J. E. Pogue, Smithsonian Institution Bull. 102, 1, p. 55; 1919.

[2] While cracking is here undesirable, cracking processes are of great commercial importance in increasing the yield of gasoline from a barrel of crude oil. See W. F. Rittman, C. B. Dutton, and E. W. Dean, Bulletin 114, Bureau of Mines, p. 5; 1916.

work their way with the kerosene past the piston rings and down into the oil in the crank case.[3] In special cases, when the piston rings are very tight and a very volatile fuel is used, there may be little or no dilution, and the oil increases in viscosity with use, as it does in a steam turbine.

Improvements in engine design have been proposed to prevent the kerosene from reaching the crank case or to distil it off continuously,[4] but these devices are not in general use, and it may be assumed necessary to remove the kerosene from used automobile oils in order to bring them back to their original viscosity. It is safe to expect that improvements in engine design will not be perfected and adopted rapidly enough to counterbalance the steady decrease in the volatility of the fuel,[5] and thus to prevent crank-case dilution.

III. PRESENT METHODS OF RECLAIMING USED OILS.

Several companies are now furnishing apparatus for reclaiming used oil either in batches or continuously. Considering first a process devised about 1915, the reclaimer comprises a double steel shell, the annular space between the two shells serving as a water jacket. A continuous supply of hot water maintains a temperature of 140 to 160° F. (60.0 to 71.1° C.) in the oil under treatment. The inside shell is filled with equal parts of used oil and water. A pound of "special coagulant" for each 4 gallons of oil is dissolved in hot water and added to the oil, which is then thoroughly agitated for 10 minutes by compressed air or otherwise. The clean oil is drawn off after the mixture has been allowed to settle for about 10 hours.

It is stated that "the effect of this coagulant is not due to chemical action, but is purely mechanical, being based on the scientific principle of relative surface tensions of oil and water." It is difficult to judge the efficiency of this system, since, in the illustration given, the used oil taken from an oil engine had a higher flash point than the new oil, showing that there was no crank-case dilution from a volatile cracked product.

Another system which is extensively employed utilizes centrifugal force to remove impurities. The oil is first heated by blowing

[3] For the nature of carbon deposits see B. S. Circular No. 99, p. 4, 1920, and F. H. Garner, J. Inst. Petroleum Technologists, April, 1921.

[4] W. F. Parish, Scientific Lubrication, 1, p. 5; 1921. W. F. Parish, J. Soc. Automotive Engineers, 7, p. 231; 1921. G. A. Kramer, J. Soc. Automotive Engineers, 6, p. 123; 1920.

[5] H. H. Hill and E. W. Dean, Bulletin 191, Bureau of Mines, p. 100; 1920. N. A. C. Smith, Bureau of Mines, Reports of Investigations, Serial No. 2272, August, 1921.

live steam into it, which removes the kerosene, and is then run through the centrifugal purifier, which removes all the water, metallic particles, and all of the carbon "except that which is in colloidal suspension." It is claimed that the colloidal carbon will not affect the lubricating qualities of the oil, but that it can be removed if desired by adding a "countercolloid" before centrifuging, a countercolloid evidently being a material to flocculate the colloids.

A continuous by-pass filtering system[6] is coming into use for keeping steam-turbine oil in good condition and thus preventing the necessity of reclaiming oil in batches. The incoming oil is heated when necessary to lower its viscosity and thus reduce its ability to retain water and solid particles in suspension. Precipitation is induced by low velocities over shallow trays, and the oil finally passes through closely woven cloth by gravity. Table 1 gives some indication of the extent to which a continuous filtration system retards the increase in viscosity and in acidity during use. It is assumed that the acidity is referred to oleic acid in both cases.

TABLE 1.—Effect on Steam-Turbine Oils of Continuous Filtration.

Test.	National Electric Light Association, without filtration.		General Electric Review, with filtration.	
	New oil.	After 9 months.	New oil.	After 30 months' use.
Viscosity Saybolt universal at 100° F.....seconds..	148	189	138	139
Acidity.....per cent..	.....	.85	.....	.25

There is need of much more data to show how much of the difference in rate of deterioration of the oil indicated in Table 1 is due to filtration and how much to a difference in the quality of the oils when new.[7] But apparently the acid tends to become segregated in the sludge, and the removal of sludge thus decreases the percentage of acidity, although the method of filtering is not a deoxidizing process, like filtering through fuller's earth in the refining of oil.

[6] Gen. Elec. Rev.; May, 1921. Report of Prime Movers Committee, National Electric Light Association, p. 8; 1921.

[7] For changes in demulsibility with use see Winslow H. Herschel, B. S. Tech. Papers, No. 86, p. 36; 1917. Demulsibility is a measure of the readiness of separation from an emulsion with water and varies inversely as the acidity.

It is evident that the above-described method of filtering will not remove kerosene and can not be applied to the more complicated task of reclaiming motor oils. The following apparatus is used in reclaiming airplane motor oils and was used in the investigation to be described later:

The purifier consists essentially of two coaxial cylindrical shells of galvanized sheet steel, the space between being heated by steam. The apparatus is covered with a conical hood, which can be easily raised or lowered by means of a counterpoise. After 100 gallons of dirty or used oil has been poured or pumped into the inner shell and the hood closed, steam at about 30 pounds gage pressure is admitted to the steam jacket until the thermometer shows a reading of from 190 to 212° F. (87.8 to 100° C.). Steam is now admitted to the inner shell, thus agitating the oil and at the same time raising its temperature to between 200 and 212° F. (93.3 and 100° C.). The necessary length of agitation depends upon the viscosity of the oil and the amount of dirt and kerosene it contains. The progress of driving off the kerosene is watched by testing samples of oil for flash point. When the flash point has reached approximately as high a value as that of the new oil it is known that the kerosene has nearly all been driven off. The maximum time generally found necessary for steaming is one hour.

According to the directions for operating the apparatus it may be necessary to finish the steam agitation of the oil at a higher pressure than 30 pounds. It is evidently impracticable, however, to drive off all the kerosene, since the end point for the highest grade of aviation gasoline [8] is 165° C. (329° F.), a temperature which could only be reached with a steam pressure of 87 pounds gage pressure. It should also be observed that the flash point of a blended oil is higher than that of the constituent having the lower flash point,[9] a fact which increases the difficulty of detecting the presence of small amounts of diluent.

After steam agitation has been completed from one-eighth to one-fourth pound of soda ash or sal soda for each gallon of oil to be treated should be thoroughly dissolved in sufficient water to obtain a saturated solution and the solution mixed with the oil. The function of the soda is to coagulate the carbon and other suspended impurities, the amount of soda required varying with the nature of the used oil, though an excess of soda does no harm.

[8] Technical Paper No. 305, Bureau of Mines, p. 3; 1922.
[9] H. C. Sherman, T. T. Gray, and H. A. Hammerschlag, J. Ind. and Eng. Chem., 1, p. 15; 1909.

After adding the soda solution the mixture is again agitated by steam for a minimum period of 15 minutes for light oils and longer for heavy oils. When using washing powders, which are said to give better results than sal soda, the steaming is the same as with sal soda, except that 5 to 15 minutes before the steaming is finished about 1 pound of washing powder to 75 gallons of dirty oil is added by sprinkling it upon the top of the oil. Some oils require as much as 4 pounds of washing powder.

The oil is now allowed to settle, 10 hours being usually sufficient for light oils. During the settling period the steam jacket is kept at a temperature of 180° F. (82.2° C.), but with heavy oils it is well to keep the temperature at from 190 to 200° F. (87.8 to 93.3° C.) or as high as is possible without agitating the oil. Samples are taken from time to time and heated to 212° F. (100° C.). The presence of moisture is indicated by foaming, and particles of carbon still in the oil can be seen by diluting with gasoline.

When the settling is completed, there will be three layers in the inner compartment—water at the bottom, then sludge, and clean oil at the top. The clean oil is drawn off by admitting water to the bottom of the purifier. It is not desirable to try to get the last pint of clean oil off the sludge, because the surface of the sludge is irregular. The clean oil in being drawn off passes over a brightly polished overflow in a thin sheet, so that it can readily be seen whether the oil is bright and clear. As soon as particles of sludge appear on the overflow the oil should be diverted to the dirty oil tank.

IV. TESTS WITH MOTOR-OIL PURIFIER.

The above-described apparatus was used through the courtesy of Lieut. Walter K. Burgess [10] in an investigation of its efficiency in restoring to airplane oils their original properties, and Table 2 shows the results obtained. The oil is drained from the crank case of the airplanes after each trip, and trips vary in length, but the average length of time in use may be estimated as not over five hours. The sludge mentioned in the last column was taken from the middle layer of the purifier.

[10] Engineer officer, Bolling Field, Washington, D. C.

TABLE 2.—Data on Results of Reclaiming Airplane Motor Oil.

Test.	New oil.	Used oil.	Reclaimed oil.	Sludge.
Flash.....°F.	518	248	473	.....
Fire.....°F.	618	536	563	.....
Viscosity, Saybolt universal at 210° F.....seconds.	130	104	115	.....
Acidoty (mg KOH per gram of oil).....	.056	.112	.056	0.222
Water.....per cent.	None.	.05	None.	17.00
Sediment.....do....	.05	2.00	1.00	15.00
Specific gravity, $\frac{15}{15}$.....	.897	.896	.898	.903
Carbon residue [1].....per cent.	2.35	1.48	1.36	1.35
Waters carbonization [1].....do....	.20	.....	.02	.....
Sulphur [1].....do....	.09	.16	.15	.11
Demulsibility, 180.....	Zero.	Zero.	(2)	Zero.

[1] The authors are indebted to C. E. Waters for the carbonization and sulphur tests and to N. Berryman, also of this bureau, for the carbon residue test.
[2] Would not emulsify.

All tests were made by the methods adopted by the Interdepartmental Petroleum Specifications Committee,[11] with the following exceptions: Tests for demulsibility were run, except in regard to temperature, according to Technologic Papers of the Bureau of Standards, No. 86, and Waters carbonization according to Circular of the Bureau of Standards, No. 99, previously referred to. Sulphur was determined according to Technologic Papers of the Bureau of Standards, No. 177, page 19, 1920.

The following method was used for determining acidity and is believed to give more accurate though higher results than the usual method. Forty grams of oil is accurately weighed and put into an Erlenmeyer flask, 100 cc of 95 per cent ethyl alcohol is added, and the contents of the flask are thoroughly agitated; 100 cc of distilled water is then added and the flask allowed to stand for 24 hours. The flask is heated to the boiling point, again agitated, and 50 cc of gasoline added. Using phenolphthalein as an indicator, the titration is made with N/10 KOH solution and the acidity calculated from the formula 1 cc N/10 solution = 5.6 mg KOH per gram of oil. A blank should be run, deducting the cubic centimeters required to neutralize the blank from the cubic centimeters required to neutralize the unknown sample.

It will be noted that the flash and fire points are higher for the reclaimed than for the used oil, but not as high as for the new oil, which is as would be expected. The viscosity of the reclaimed oil could be less readily foretold, because the kerosene which is not entirely eliminated tends to reduce the viscosity, and the oxidation of the oil tends to raise the viscosity. A longer period

[11] Technical Paper 298, Bureau of Mines, 1922.

of use would be necessary to tell from the change in viscosity whether or not the oxidation was excessive.

Table 2 shows that both the carbon residue and Waters carbonization were considerably reduced by reclaiming. On the other hand, the sediment in the reclaimed oil is much higher than in the new oil, probably due to taking off too large a quantity of the reclaimed oil in an endeavor to increase the yield. This observation led to an examination of the amount of sediment in the oil at different depths in the purifier, with the results given in Table 3.

TABLE 3.—Examination of Samples Taken at Intervals During Drawing Off of Reclaimed Oil.

Test.	Sample No. 1.	Sample No. 2.	Sample No. 3.	Sample No. 4.
Acidity ..... mg KOH..	0.11	0.11	0.11	0.17
Carbon residue ..... per cent..	1.53	.....	1.56	.....
Viscosity Saybolt, universal at 210° F ..... seconds..	110	105	110	310
Sulphur ..... per cent..	.21	.21	.21	.21
Carbonization ..... do....	.03	.....	.03	.....
Sediment ..... do....	.01	.01	.01	.03
Water ..... do....	None.	None.	None.	2.0

The increase in values of the last column shows the danger in attempting to reclaim too high a percentage of the oil. It is much better to return the tailings to the used oil tank and treat this with the next batch, the high values showing that the sludge from the middle layer in the purifier was beginning to come off with the oil.

V. ORGANIC ACIDITY.

The oil of Table 2 was not used long enough to develop much acidity, and the acidity was reduced to that of the new oil by the process of reclaiming. With automobile oils which are used for longer periods of time and which develop a higher acidity there is more difficulty in reducing the acidity, and the question therefore arises whether this is necessary.

It had previously been supposed that all oils high in acidity would be low in demulsibility or resistance to emulsification, but this opinion was based entirely on tests made on eastern oils. When California oils were investigated, it was found quite possible to have an oil high in acidity and yet high in demulsibility. That is, of two oils of the same acidity, one from the East and one from California, the latter would have the higher demulsibility.

This is shown by a comparison of data previously obtained from eastern oils [12] with Table 4 for California oils.

TABLE 4.—Properties of Lubricating Oils from California Crude Oils.

Oil No.	Acidity.	Demulsibility, with water, 130° F.	Viscosity, Saybolt universal at 100° F.	Number of drops.[1]
	Mg KOH		Seconds.	
1	1.30	240	339	41
2	1.05	200	380	36
3	1.08	600	280	35
4	1.34	60	280	35
5	1.51	228	96	24
6	0.62	120	465	35
7	1.09	90	335	37
8	1.20	168	209	41
9	0.76	104	470	39
10	0.67	163	195	43
11	1.15	120	392	45

[1] Obtained with a Gardner and Holdt interfacial tension apparatus. The interfacial tension is inversely proportional to the number of drops in a given volume, as explained later.

It should not be assumed that the acidity of all California lubricating oils would average as high as in Table 4, the oils for which were selected to show the relation between acidity and demulsibility, yet there is no doubt that the average California oil is much higher in acidity than the average eastern oil. The question to be decided is whether the California oils contain the same or an equally undesirable acid as the eastern oils.

In all cases the demulsibility when run with normal NaOH solution in place of distilled water was zero, and the corrosion test gave a negative result. It was noted in making the demulsibility tests with water that in many cases the oil separated quickly but incompletely from an emulsion, and this brought to mind the contention of Conradson [13] that completeness of separation is an important property of the oil which ought to be tested by determining the percentage of water in the upper layer which separates out from an emulsion. This idea is carried out in the Government methods for testing petroleum products.[14]

It is desirable that oils should have high demulsibility or separate readily from water, both in order that they may not cause trouble by emulsifying in use or in being reclaimed. But if the oil is noncorrosive and it separates rapidly and completely enough from an emulsion, then the desirability or undesirability of high acidity must be based on other grounds.

[12] B. S. Tech. Papers, No. 86, p. 28; 1917.

[13] P. H. Conradson, Proc. A. S. T. M., **16**, part 2, p. 273; 1916.

[14] Method 300.4 (Technical Paper 298, p. 40), for obtaining water by centrifuge, is for use in this connection.

In some English experiments [15] petroleum acid was produced by blowing air through neutral filtered spindle oil heated to a high temperature (360 to 400° F., 182 to 204° C.) to accelerate the oxidation. To the oil thus prepared was added the prescribed amount of oildag, and it was found that the presence of 0.1 per cent of petroleum acid caused complete precipitation of the graphite in five hours. More important considerations are the possible reduction in coefficient of friction due to the use of an oil of high acidity or, on the other hand, an increase in the rate of oxidation in use.

VI. INTERFACIAL TENSION.

The question of organic acidity has been in a chaotic condition ever since Wells and Southcombe [16] found that certain organic acids added to a petroleum oil in minute quantities had the effect of considerably reducing the coefficient of friction. They used organic acids derived from fatty oils, and they emphasize the point that all organic acids do not have the effect of decreasing the interfacial tension between the lubricant and the bearing metal and thus decreasing the coefficient of friction.

It is interesting to observe that while the use of compounded oils in steam-engine cylinders is a well-established practice, compounded oils are practically never used in internal-combustion engines in the United States, although their use in such engines appears to be well established in England.[17] It can not be assumed without further evidence that the petroleum acids will be as advantageous as the organic acids derived from fatty oils, the term "petroleum acids" being used for the unidentified acids to be found in petroleum oils which are free from fatty and mineral acids. It is possible that if a certain amount of acidity is desirable a compromise would have to be made between too much acid which would be an indication of a "gummy" oil and too little acid which would prevent the attainment of the lowest practicable coefficient of friction.

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[15] Bull. No. 4, Dept. of Scientific and Industrial Research, p. 20; 1920.

[16] H. M. Wells and J. E. Southcombe, J. Soc. Chem. Ind., p. 51 T; 1920. Winslow H. Herschel, J. S. A. E., 10, pp. 31, 369; 1922.

[17] Geo. H. Hurst, Lubricating Oils, Fats, and Greases, p. 323; 1911.

Pending the construction of a suitable oil-friction testing machine the apparatus of Donnan,[18] as used by Wells and Southcombe, was used to determine the effect of variations in organic acidity upon the interfacial tension. With this apparatus drops of oil are released under water, and the relative interfacial tension of different oils is indicated by the size or number of drops in a given volume. It was found that the apparatus gave somewhat discordant results. This was attributed to the impossibility of keeping the end of the capillary absolutely clean, and somewhat better results were obtained after the end had been tapered to a thin edge.

Since making the required samples by isolating the acid and adding it to a neutral oil in various proportions would have been, if possible, a prolonged operation, the samples were prepared by mixing in various proportions an oil of high acidity with one of low acidity. It was at first assumed that a used oil would be suitable for the oil of high acidity, but one which was discarded as unfit for further use in an engine gave an acidity of only 0.20 mg KOH. This showed 62 drops in the interfacial tension apparatus. The oils used in blending were, (A) a class B oil purchased on Government specifications, (B) an eastern oil of unusually high acidity which had emulsified when used in an automobile, and (C) lard oil several years old, the same sample as used by Bingham.[19]

The viscosities of blends of oils A and B did not vary more than the experimental error, the corrosion test showed negative results, and the demulsibility was zero for acidities of 0.33 mg KOH and over. With blends of oils A and C the viscosity, Saybolt Universal at 25° C. (77° F.), varied from 1,134 seconds for oil A to 338 for oil C. The demulsibility was reduced to zero by the addition of 12.5 per cent of the lard oil. A compound with 37.5 per cent of lard oil with an acidity of 2.69 mg KOH showed slight corrosion, and higher acidities showed much greater corrosion. The comparison of acidities and number of drops obtained with the interfacial tension apparatus is shown in Table 5.

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[18] F. G. Donnan, Zs. f. Physik. Chem., **31**. The apparatus as made in the United States is illustrated in paper by H. A. Gardner and P. C. Holdt, Circular 124, Paint Manufacturers' Assoc. of the U. S., p. 6; May, 1921.

[19] E. C. Bingham, B. S. Tech. Papers, No. 204, p. 59; 1922.

TABLE 5.—Interfacial Tension of Oils of Various Acidities.

BLENDS OF OILS A AND B.

Oil A (per cent).	Acidity (mg KOH).	Number of drops.	Oil A (per cent).	Acidity (mg KOH).	Number of drops.
100	0.04	66	50	0.45	73
95	.08	70	45	.48	73
90	.12	77	40	.52	75
85	.17	80	35	.56	76
80	.20	82	30	.59	76
75	.22	85	25	.61	77
70	.28	85	20	.68	75
65	.32	76	15	.72	76
60	.33	73	10	.76	70
55	.40	71	5	.80	67
			0	.84	57

OIL A COMPOUNDED WITH OIL C.

100.0	0.04	66	37.5	4.59	95
87.5	1.12	110	25.0	5.47	86
75.0	1.85	113	12.5	6.38	95
62.5	2.69	111	0.0	7.28	102
50.0	3.66	95			

Table 5 shows a decrease in interfacial tension due to the addition of lard oil, but results with blends of oils A and B are inconclusive. Apparently either the apparatus is not accurate enough to detect the slight differences in acidity between different samples or the petroleum acids in different oils were not the same, and the effect of blending different unknown acids in varying proportions can not be foretold.

VII. REFINING PROCESSES.

The acidity of a lubricating oil may be due to acidity of the crude oil or may be developed during the process of refining. Acidities of crude oil are not ordinarily reported, but they are apparently relatively low. Three samples selected at random showed acidities of 0.11, 0.06 and 0.06 mg KOH for Texas, Mid-continent, and Pennsylvania crudes, respectively. If there was no reduction of acidity due to the refining, the acidity of a lubricating oil would be much greater than that of the original crude on account of the concentration of the acid of the crude in the much smaller volume of the lubricant.

The process of refining must necessarily vary with the nature of the crude oil, but it consists in general of distilling off the lighter portion from which fuels are made and continuing the process to obtain the lubricating oils distillate. This distillate is separated by a second distillation into fractions of different

viscosities, and the fractions are treated with sulphuric acid and neutralized with caustic soda, the soda apparently acting to precipitate impurities as well as to neutralize the acid left in the oil. Filtration through fuller's earth serves a similar purpose to the acid treatment. In the case of oils containing much oxygen a preliminary treatment with soda before distillation may be beneficial,[20] and where there is considerable sulphur in the crude it may be necessary to redistil after acid treatment and neutralization. The most probable action of this redistillation is to break up the compounds formed by the action of the sulphuric acid on some of the constituents of the oil and allow the sulphur dioxide to escape.

A certain amount of cracking as well as oxidation is unavoidable in refining, although ordinarily steam is introduced to prevent the cracking as much as possible, and in some cases a vacuum is employed for the same purpose. It is reasonable to suppose that an oil which will oxidize or disintegrate more readily than another in refining will also deteriorate more rapidly in use.

Since acidity is developed during oxidation, an acidity test may be used as an indication of the resistance of the oil to oxidation or of the adequacy of the acid treatment or filtration to reduce the acidity thus formed or that originally present in the crude. It might appear at first sight that the acidity test is of small value in the case of an automobile oil, since the acidity is increased (or the demulsibility reduced) after a very short time in use, but this reasoning is not valid. The difference in chemical stability of the original oils still remains. If all of a series of oils will emulsify, it proves that the acidity is at least equal to the minimum value required to cause emulsification, but not that all of the series are of equal acidity or that all will deteriorate with equal rapidity.

Adequate filtration or great care in the removal of the sludge formed in acid treatment will produce an oil which will be satisfactory as regards acidity or demulsibility. Only 0.1 per cent of the acid sludge left in the oil would reduce the demulsibility from 1,200 to 300. Acid treatment is also said to reduce the carbon residue, a test which may be used to detect oils made by blending light oils with unfiltered cylinder stock.

It is apparently more difficult to reduce the carbonization value, which in general is higher for naphthene base oils and for

[20] B. Redwood, A Treatise on petroleum, 2, p. 523; 1922.

oils of low viscosity,[21] while the carbon residue is higher for paraffin base crudes and for oils of high viscosity. Whether or not the carbonization value can be controlled except by choice of crude has no bearing upon the desirability of oils showing a low carbonization value or a high resistance to oxidation.

VIII. THE CAUSE OF SLUDGE FORMATION.

Failure of lubrication is due primarily to one of two causes. Either the lubricant becomes so low in viscosity from dilution or from excessively high temperatures that it can not prevent metallic contract, or it may fail to reach the rubbing surfaces because it is too viscous or full of sediment or sludge to pass through the oil passages. The choice of an oil of suitable viscosity when new and a sufficiently frequent removal of the diluent will guard against the first form of failure. An emulsifying oil may cause failure from the second cause, even if sludge and sediment are not formed, because emulsions are more viscous than the oils from which they are made.

It is not certain whether sludge should be regarded as an emulsion or as an oxidation product, since the conditions are favorable for the formation of both. The metallic particles from the bearings are in a finely divided state and suited to cause catalytic oxidation of the oils.[22] Waters has also found that organic sulphur compounds present in the crude oil and not removed by refining will increase the rate of oxidation, although they can not be detected by the corrosion test. Elsewhere he remarks:[23]

> Transformer oils are regarded as undesirable if they contain more than a very small portion of sulphur, because this element is believed to attack the wires and also to increase the tendency to form sludge. * * *. No oil which contains much sulphur will have a low carbonization value.

These quotations suggest the use of the tests for sulphur or Waters carbonization to select an oil which would not be apt to form sludge or to determine whether or not reclaimed oils had been restored to as good a quality as when new. While the test for acidity is simpler, it is doubtful whether it would serve the same purpose, since there does not appear always to be a marked correlation between acidity and carbonization,[24] though Waters [25]

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[21] W. F. Parish, J. Am. Soc. Nav. Eng., 32, p. 55; 1920.
[22] C. E. Waters, J. Ind. and Eng. Chem., 13, p. 901, 1921, and 14, p. 725; 1922.
[23] C. E. Waters, B. S. Tech. Papers, No. 177, p. 8; 1920.
[24] B. S. Tech. Papers, No. 86, p. 28.
[25] C. E. Waters, B. S. Tech. Papers, No. 73; 1916.

found that acidity and carbonization both increased when oils were exposed to sunlight.

A sludge is unlike an emulsion in that it does not form suddenly but only after the oil has been subjected to prolonged use, and the formation of sludge would therefore appear to be due to changes in the oil which gradually develop. The changes which are known to occur are: (*a*) Accumulation of metallic particles, (*b*) accumulation of dust, (*c*) in the case of internal-combustion engines the accumulation of "carbon" from the cylinders, and (*d*) oxidation of the oil, accompanied by an increase in acidity and the formation of oxidation products of a tarry or asphaltic nature.

Of the four possible causes of sludge formation (*d*) is the only one which depends upon the lubricant. It is not certain just how oxidation acts to cause sludge or whether or not sulphur exerts an influence. There appear to be two general possibilities. First, the nucleus of a particle may be a drop of water which is surrounded by colloidal carbon, the oxidation product serving as a binder to make the carbon into a continuous coating, so that the drops are prevented from coalescing. Again, the nucleus may be a particle of carbon or road dust, to which the oxidation products adhere. When the sticky particles coalesce into sufficiently large masses to be visible or to be precipitated, the material is called sludge. Examination with a microscope seemed to indicate from the lack of angularity of the nucleus that it was a drop of water, and that therefore sludge formation was a case of permanent emulsion due to colloids or finely divided solids.[26] However this may be, either supposition in regard to the formation of sludge would point toward the necessity of removing carbon, road dust, oxidation products, and a possible need of reducing the acidity and sulphur content.

Table 6 shows results of the examination of several sludges. The material was removed from the turbine oil by a centrifuge, it was precipitated from the crank-case oil by gravity, and the sludge from the transformer oil was a fairly solid mass that adhered to the core of the transformer. The last column gives data on the oil from which the crank-case sludge was precipitated.

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[26] See T. R. Briggs, J. Ind. and Eng. Chem., 13, p. 1008; 1921.

TABLE 6.—Analysis of Sludges.

Material.	Turbine sludge.	Transformer sludge.	Crankcase. sludge.	Used oil.
	Per cent.	Per cent.	Per cent.	Per cent.
Oil	48.90	65.10	31.54	74.09
Tarry matter	14.22	4.20	.46	.06
Volatile	11.54	4.56	62.68	25.40
Carbon	6.56	25.44	3.98	.24
Ash	18.64	.48	1.12	.16
Total	99.86	99.78	99.78	99.95
ANALYSIS OF ASH.				
SiO^2	42.22	12.08	9.54	37.50
$Fe_2O_3+Al_2O_3$	35.27	37.14	82.46	62.50
CaO	Trace.	9.60	2.31	Trace.
MgO	Trace.	Trace.	Trace.	Trace.
Cu	6.83	33.92	2.71	.....
Pb	2.46	5.42	1.05	.....
Ni	.....	Trace.	Trace.	.....
Zn	6.45	.....	.....	.....
Total	93.23	98.16	98.07	100.00
Total sulphur	.33	.21	.77	.56

The amount of silica in the steam-turbine oil sludge is surprising. As the turbine had been in use for several years, it is hard to believe that the silica came from the core sand of the turbine casing, and it is also difficult to believe that it came from the dust in the atmosphere of a power station. The transformer oil sludge is due to different causes [27] and is presented only for comparison. The amount of copper in the ash is noteworthy.

IX. CONCLUSIONS.

1. Used oils should be judged by the same tests as are applied to new oils and will be equally serviceable.

2. The present methods of reclaiming oil are successful as far as the generally recognized tests are concerned, and improvements are limited by lack of knowledge concerning what additional tests are needed to make sure that oils, whether new or reclaimed, possess those properties which make them suitable when new and durable in use.

3. Further investigation is needed concerning the value of the tests for acidity, sulphur, and resistance to oxidation.

WASHINGTON, July 5, 1922.

[27] See paper by C. J. Rodman presented before the American Electrochemical Society, p. 105; 1921.

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